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of Engineers

DREDGING RESEARCH PROGRAM

TECHNICAL REPORT DRP-97-1

DEVELOPMENT AND VERIFICATION OF AN INTRUSIVE HYDROGRAPHIC SURVEY SYSTEM FOR FLUID MUD CHANNELS

by

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- Area 1 - Analysis of Dredged Material Placed in Open Water
- Area 2 - Material Properties Related to Navigation and Dredging
- Area 3 - Dredge Plant Equipment and Systems Processes
- Area 4 - Vessel Positioning, Survey Controls, and Dredge Monitoring Systems
- Area 5 - Management of Dredging Projects

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US Army Corps
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Dredging Research Program Report Summary



Development and Verification of an Intrusive Hydrographic Survey System for Fluid Mud Channels (TR DRP-97-1)

ISSUE: Certain waterways maintain a state of unconsolidated fine-grained sediments along navigation channel bottoms, generally referred to as fluff, or fluid mud. Fluid mud can obscure conventional acoustic depth signals. To improve the accuracy of channel depth measurements in fluid mud channels, a non-acoustic system was needed.

RESEARCH: An intrusive gauge was designed to follow a firm bottom as it was towed behind a survey vessel. The towed gauge program involved a development and verification phase.

Development: A towable gauge was designed with an adjustable ballast to follow a bottom depth according to prescribed sediment density properties.

Verification: The towed gauge was designed to measure depth, but the verification phase included other sensors, notably nuclear density measurement. An additional separate sediment sampling program was included to

measure sediment strength associated with a given density horizon measured by the towed gauge.

SUMMARY: Field trials verified that the towed gauge followed quasi-constant density horizons. Sediment strength (viscous forces) also influenced the depth and density recorded by the towed gauge. The towed gauge resulted in an intrusive survey method that can significantly improve depth measurement accuracy in fluid mud channels.

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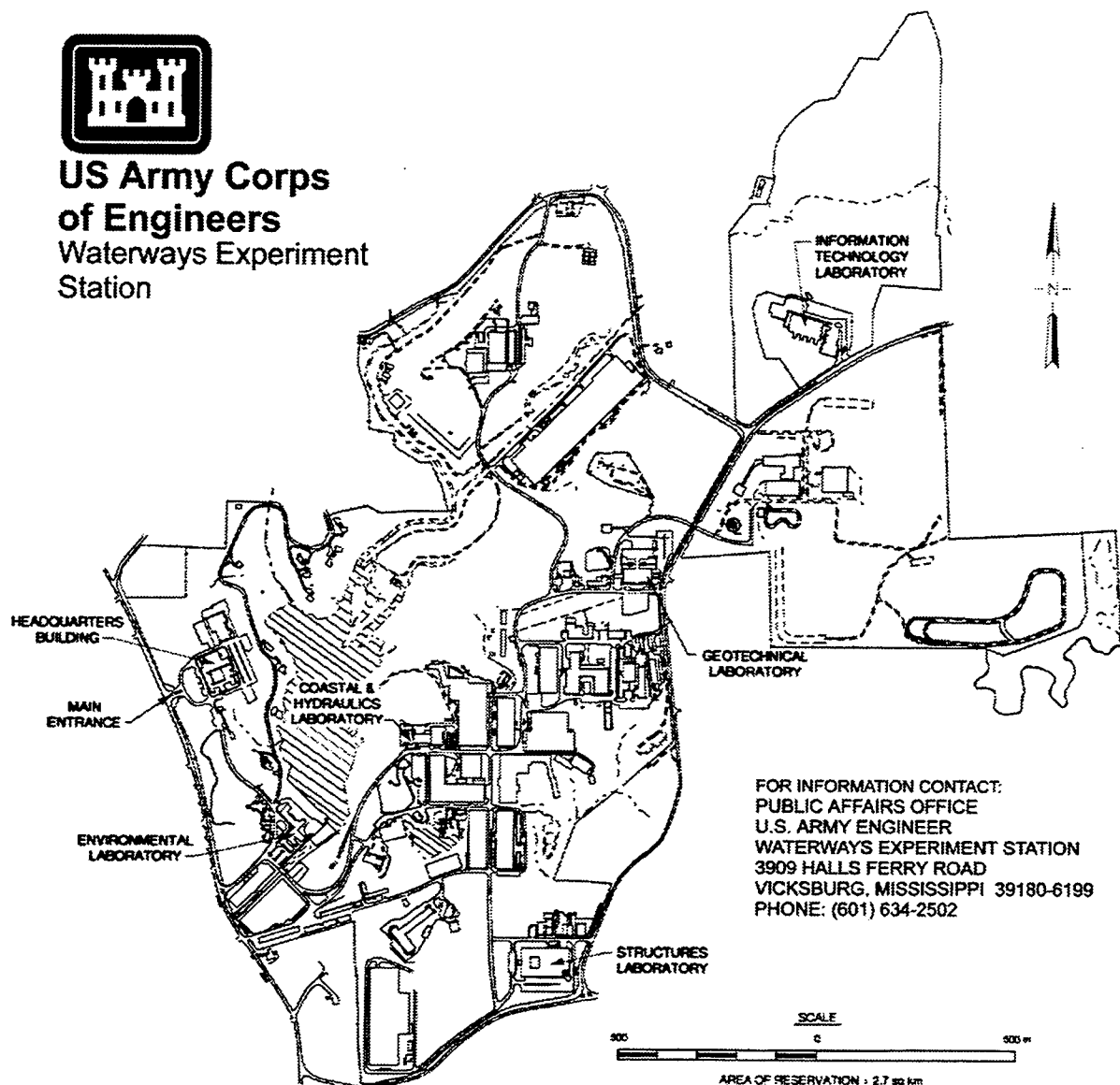
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Preface

This report documents research conducted under the Dredging Research Program (DRP), Technical Area 2 - "Material Properties Related to Navigation and Dredging" sponsored by Headquarters, U.S. Army Corps of Engineers General Investigation Program. The individual work unit was titled "Measurement and Definition of Navigable Bottom in Fluff and Fluid Mud."

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Summary

This report describes the development and field verification of a new hydrographic surveying system for fluid mud channels. The new surveying system was developed as the primary product of the "Measurement and Definition of Navigable Bottom in Fluff and Fluid Mud" work unit under the U.S. Army Corps of Engineers Dredging Research Program.

A rapid, precise, and above all, accurate survey system for fluid mud channels was required under this work effort. At the onset of work, European experience was studied. Although the system was not designed to operate like the fluid mud evaluation systems used in Europe, application of an intrusive gauge was considered to be the only reliable depth evaluation approach.

Conventional acoustic depth-sounding systems will continue to provide the bulk of channel bottom evaluations. However, special problems encountered in fluid mud channels warrant an intrusive gauge system. Acoustic depth interpretations, including variable frequency systems, in fluid mud channels have resulted in controversy for assuring depths for vessel traffic and evaluating dredging operations. Upper fluid mud layers in a channel can return a bottom sounding at a level shallower than a ship's draft traversing the channel. Fluid mud layers may also be present before and after dredging operations, obscuring acoustic records and resulting in payment claims.

The new fluid mud surveying system includes a towable sled that provides prima facie evidence of any material resistance encountered while returning a firm bottom level. The sled system has been field tested in three fluid mud channels along the Gulf of Mexico that have a history of the fluid mud channel problems mentioned above. The system goals of developing a rapid and accurate fluid mud channel depth surveying system were met by the sled.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
horsepower (550 foot-pounds (force) per second)	745.6999	watts
inches	25.4	millimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
pounds (force) per foot	14.5939	newtons per meter
square feet	0.09290304	square meters

1 The Fluid Mud Problem

General

To monitor sedimentation rates and shoaling conditions in navigation channels, the U.S. Army Corps of Engineers (USACE) regularly completes and reviews hydrographic surveys. Hydrographic surveying results also define dredging needs, verify post-dredging channel dimensions, and, in many cases, determine payment for contract dredging. With the development of the Global Positioning System (GPS) satellite network, both horizontal and vertical position can be accurately acquired within centimeters at the survey vessel. However, GPS signals do not work through water columns, and overall survey accuracy depends heavily on depth measurement accuracy.

Early hydrographic surveyors recognized soft, unconsolidated fine-grained bottom sediments by using sounding poles and weights. As acoustic depth sounders were introduced through the 1940's and 1950's, soft bottom sediments resulting in channel sounding difficulty were described as "fluff" or fluid muds (Scheffauer 1954).

Identifying Fluid Mud

In hydrographic surveying terms, fluid muds are soft bottom sediments having an upper surface that appears as a well-defined, smooth, but often "ghost-like," return on a fathometer (Krone 1972). Acoustic fathometers do not measure the depth to a given sediment density. They detect sharp gradients in density, which can occur at any sediment-water density. Therefore, they cannot be used to reliably define a constant density horizon in fluid mud.

Figure 1 shows an early acoustic bottom record interpreted as "true bottom and fluff" (Scheffauer 1954). The fluff in this case was defined as fine-grained materials suspended above the channel bottom. It is unknown whether the lower fluid mud boundary described as true bottom was verified, or simply accepted as recorded by the fathometer. Chapter 2 of this report explains the need to verify the sediment stiffness associated with an acoustic depth record such as in Figure 1.

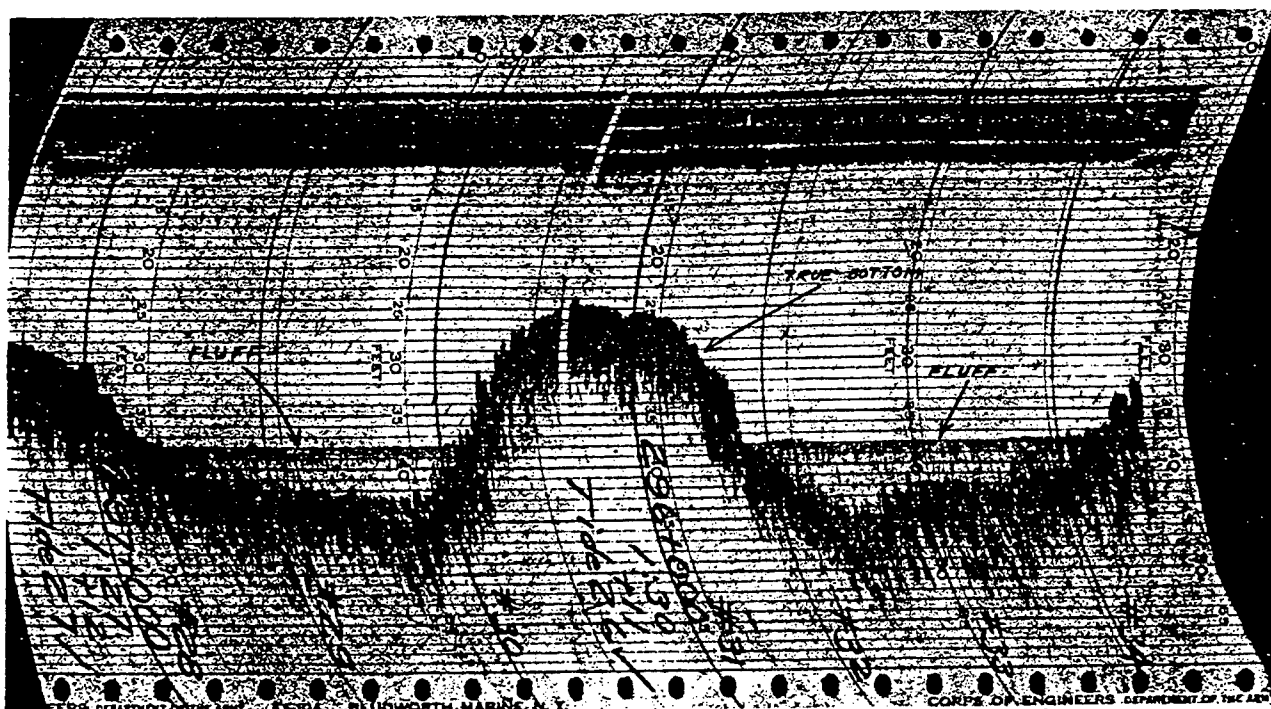


Figure 1. Fathometer chart showing true bottom and fluff lines

European concepts (Appendix A) include defining fluid mud limits with a density-based *nautical depth* for the lower boundary of the water column. This definition links navigation and maintenance dredging to measuring density on a regular basis to determine channel bottom. A nautical bottom can be defined more exactly based on mud properties, including the effect on vessel maneuvering characteristics (Permanent International Association of Navigation Congresses 1989). European projects practicing a density-based nautical depth maintenance schedule have developed density criteria with deep-draft vessel tests.

Fluid Mud Characteristics

Fluid muds occur with density gradations ranging from slightly greater than that of the overlying water in its upper layers to that of stiff, dense lower layers. Fluid mud densities can range from 1.05 to 1.35 g/cc. Concentrations of these muds range from 50 to 500 g/l or 2-13 percent solids by volume. Fluid muds contain silt and clay-sized materials with clay minerals and organic matter. Importantly, fluid muds have density transition points at which viscosity, shear modulus, and yield stress increase sharply. This characteristic was exploited in the development of the Dredging Research Program (DRP) intrusive survey system (Chapter 2).

Thick layers of fluid mud occur at some times and at some places, especially in estuarine areas where fine-grained sediments are frequently resuspended or trapped. Fluid muds generally form a lutocline, or area of steep vertical density gradient. Gravity forces tend to consolidate fluid mud layers while ambient currents and waves can randomly resuspend layers. Deep-draft vessel propwash also significantly disturbs and resuspends fluid muds (Mathew and Chandramohan 1993). These forces can constantly change the density layer elevations within fluid mud on channel bottoms. Unlike sands, fine-grained fluid muds are slow to consolidate and can persist in a fluid-like state for long periods.

Channels where fluid mud is likely to collect have moderately high flows with maximum current speeds of 1-3 ft per sec (fps) but with very small net tidal-averaged current speeds. Moderate flow speeds maintain conditions suitable for fluid mud but are unable to completely entrain and disperse the material. Fluid mud can flow or can remain stationary and gradually consolidate by settling into a solid sediment bed.

Defining Fluid Mud

In this report, the upper level of fluid mud is defined by a high-frequency acoustic fathometer and the lower level, or bed, is based on two properties, density and viscosity. Of these properties, density is more readily field measurable. Past difficulties with surveying and, therefore, defining fluid mud include prescribing limits for rheologic properties and the lack of equipment to rapidly meter those properties in the field. Field trials (Chapter 3) demonstrate the importance of determining the sediment strength at a given fluid mud density. The density and viscosity values that establish channel bottom data in Chapter 3 offer a conservative fluid mud definition.

Purpose

The fluid mud survey system described here was designed to provide better navigability assessments and dredging volume estimates in channels containing fluid mud. This report presents a surveying system that will define fluid mud based on its rheologic properties.

Report Scope

Fluid mud channel dredging volume estimates are discussed based on conventional soundings and a new depth evaluation system using a towed gauge. The towed gauge system field trials demonstrate the level of improved accuracy and compare instrument precision to acoustic depth soundings. Survey instrument design, development, and field applications are included. This

report was written specifically for those knowledgeable in the areas of hydrographic surveying and acoustic fathometer operation.

2 Developing the Prototype Surveying Device

General

In addition to removing the bottom depth uncertainties presented by acoustic fathometers, it was necessary to design the towed gauge into a system operated simultaneously with an acoustic fathometer. Several design considerations led to including acoustic records with the towed gauge system: (a) acoustic records were necessary for comparison to existing, questionable surveys, (b) most waterway managers were interested in comparing acoustic results with a given intrusive technique, and (c) the new system needed a means to detect the presence of fluid mud. Attention was given to acoustic measurement since the DRP gauge was designed to operate as both a stand-alone survey tool and verification for acoustic survey practices. Acoustic soundings are discussed as they pertain to fluid mud surveys and the DRP towed gauge system development.

Acoustic Depth Measurement in Fluid Mud Channels

Fathometers detect changes in acoustic impedance as the instrument sound beam, or pulse, passes through the water column. The rapid change in impedance encountered when the sound beam reaches bottom causes part of the beam to be reflected back to the source. The increase in density encountered when the sound wave reaches solid bottom sediments contributes the major part of the impedance change. The elapsed time between the origin of the beam and receipt of reflection determines depth. Standard onsite calibration procedures account for sound speed variations in the water column. Accurate bottom depths are normally recorded for well-defined bottom gradients such as sands or consolidated muds. However, fluid mud channel bottoms can present layers of varying sediment densities, or impedance gradients, over vertical distances up to several meters. Fathometers erroneously define bottom in fluid muds at

one or more gradients based largely on their acoustic operating frequency. Multi-frequency fathometers often define multiple erroneous bottom profiles.

Acoustic Signal Frequency

Acoustic sounding penetration is largely determined by the sounding frequency. High-frequency fathometers (at or approximately 200 kHz for the purposes of this report) are very precise, or repeatable depth-sounding instruments. In fluid muds, a high frequency will likely return acoustic pulses where only a slight change in impedance is encountered. High-frequency fathometers have recorded bottom along 1.05 g/cc density horizons. In estuarine waters with an ambient density of roughly 1.00-1.02 g/cc, a density transition of 1.05 g/cc would not indicate a firm bottom, but rather muddy water. Low-frequency fathometers (20-40 kHz for the purposes of this report) operate with acoustic pulses that suffer less from attenuation than the higher frequency pulses (Ingham 1984). Therefore, the low-frequency equipment might well return a bottom level several meters below that of a high-frequency unit in fluid mud (Figure 2).

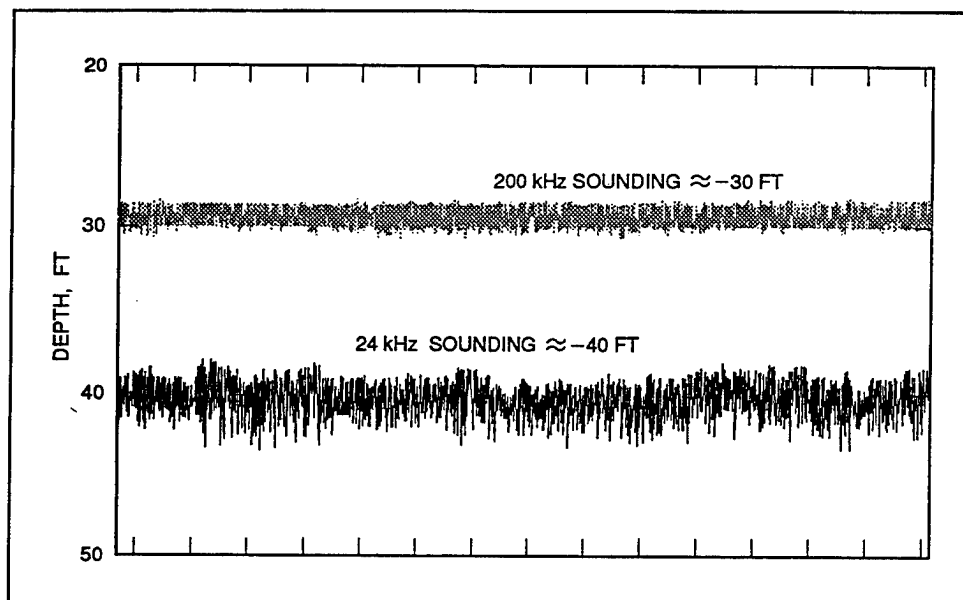


Figure 2. Dual-frequency acoustic sounding along Gulfport Channel center line

Other Influences

A certain amount of an acoustic pulse penetrates bottom sediments. If the pulse was sufficiently powered, echoes might be returned from different layers of sediment in addition to or instead of the uppermost layer (Ingham 1984). This explains the ghost-like shades referred to by Krone (1972) and depicted in

Figure 1. Common practice involves adjusting signal strength to display a clear bottom interface without double or multiple echoes. Multiple echoes are known to yield a depth two, three, or more times the actual bottom depth. A slight change in signal strength may not produce a multiple echo in fluid muds, but may change the recorded gradient level within a few inches to within a few feet, resulting in ghost-like bottom depths such as in Figure 1.

The Need for Intrusive Depth Evaluation

Figure 3 shows high- and low-frequency acoustic return in a fluid mud channel and the elevation of weighted sampling equipment lowered to the "bottom." The sediment strength supporting the approximately 35-lb¹ sediment sampler was significantly different from the impedance gradients recorded with the fathometer. Figure 3 highlights the need to evaluate sediment stiffness at acoustically recorded depths in fluid muds.

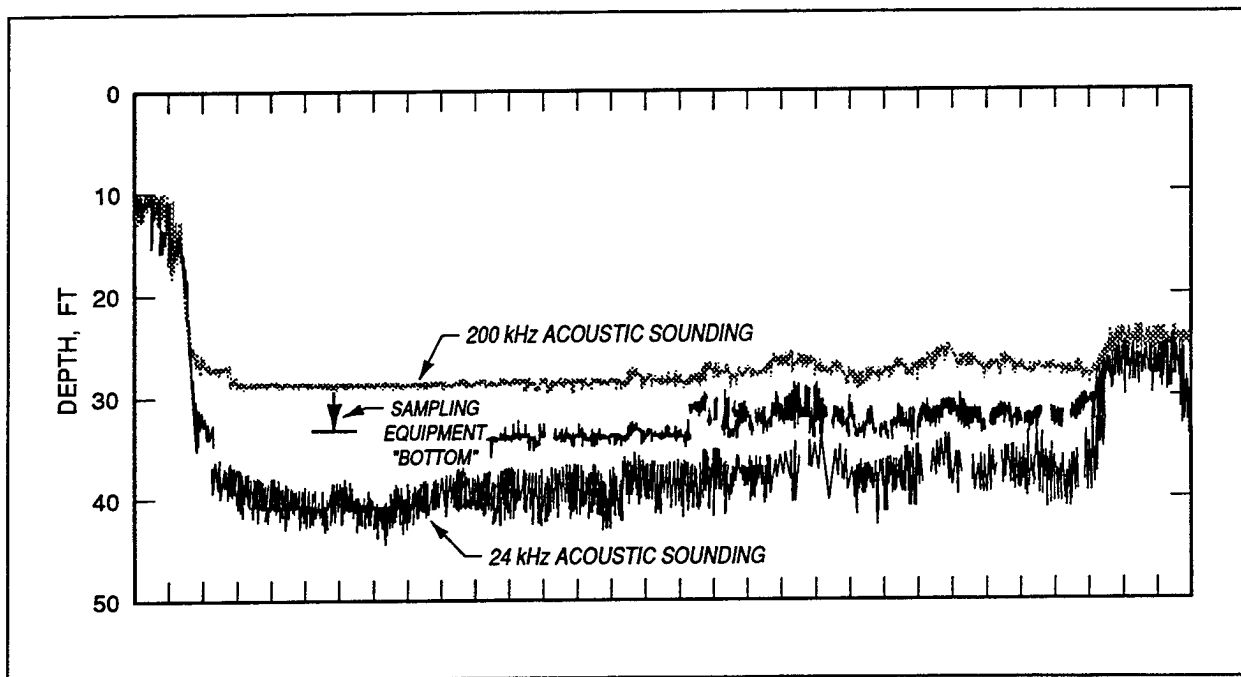


Figure 3. Acoustic return in a fluid mud channel

Equipment manufacturers have attempted to solve some of the surveyor's dilemma by offering fathometers simultaneously sounding different frequencies, usually dual-frequency units with high frequencies around 200 kHz and low frequencies from roughly 20-40 kHz. Dual-frequency equipment can usually

¹ A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page ix.

detect a fluid mud condition, but adjusting signal strengths for each frequency while attempting to resolve "bottom" over several meters of depth implies lowering an intrusive gauge.

Towed Sled Description

The towed sled operating principle was to establish a continuous horizontal firm or navigable depth plane based on the frictional and supportive mud forces it encountered *as it was towed along fluid mud channel bottoms*.

Figure 4 is a schematic drawing of the sled. The static weight of the sled is about 260 lb in air and 60 lb in water. The frontal area of the sled is about 1 sq ft, and the volume of the sled is about 3 cu ft. The top-view projected area is about 12 sq ft.

The tow cable has a diameter of 0.9 in. with a submerged weight of 0.7 lb/ft. The cable tow termination is 4 in. outside diameter (OD) by 2 ft long with a jaw end. The submerged weight of the termination is about 40 lb, and is where the tension link and tow angle indicator are located. The bridle crosspiece is 1.5-in. OD stainless steel, and the cable conductor splice is 4 in. OD. Figure 5 is a photograph of the sled and the components described.

The tow cable is led over a 36-in.-diam block to an electro-hydraulic winch. The 5-hp winch is equipped with a slip ring cable conductor connection, and has the capability for computer control.

There is, of course, always the possibility that the sled could jam against an object on a channel bottom, and the sled and tow cable system was designed with features to minimize the possibility of jamming. The deployment system incorporates (a) a bridle system that can flip the sled over an obstruction, (b) an automatic slip clutch winch, which allows the cable to pay out after a 2,500-lb load is exceeded, and (c) an acoustic beacon to be used if the sled must be located and manually retrieved by divers. Sled components were machined from stainless steel and a tough high-density polyethylene. All major component connections were either welded or bolted to withstand the rough and abrasive environment along channel bottoms.

Sled Transducers

The transducers listed in Table 1 are mounted in or on the sled.

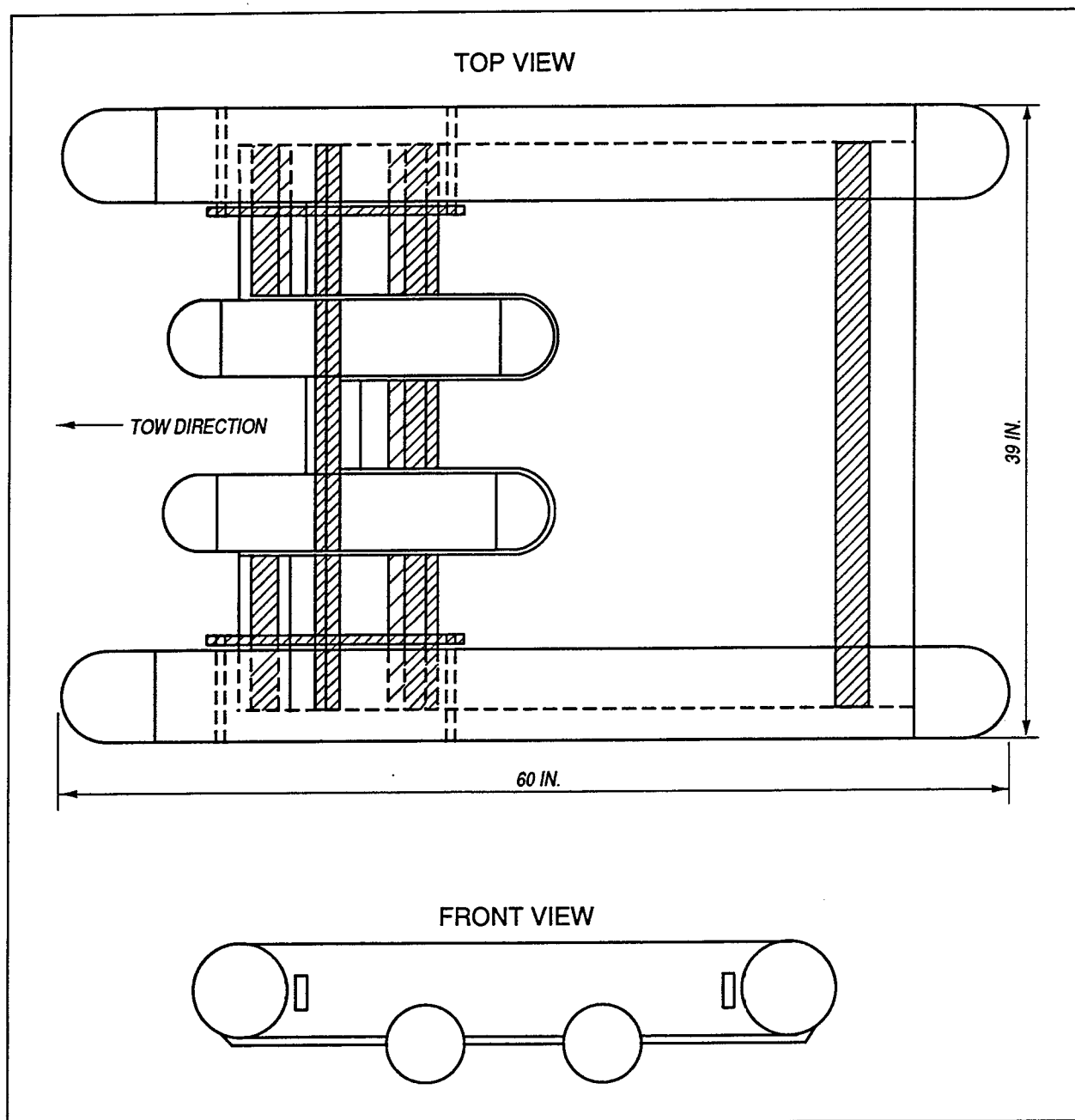


Figure 4. Schematic drawing of the sled showing front and top views

Prior to any field tests, the sled was tested in a large, high-velocity recirculating flume facility at the Iowa Institute of Hydraulic Research, Iowa City, IA. The submerged specific gravity of the sled was ballasted to 1.15 g/cc. The tubular sections of the sled (Figures 4 and 5) were designed for adjustable ballasting, and 1.15 g/cc was chosen as a conservative starting point for field density transition evaluation.

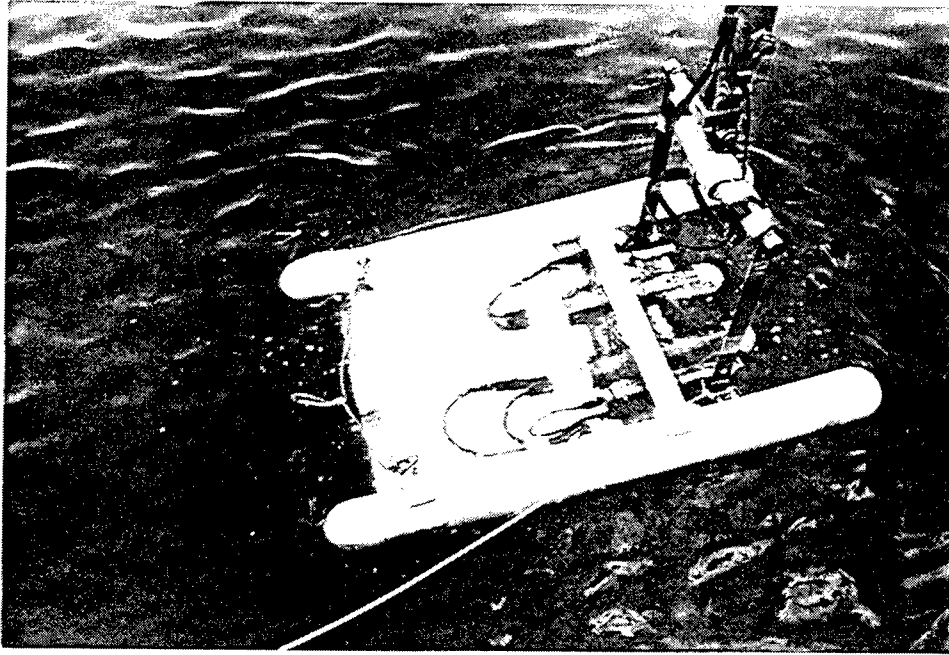


Figure 5. Sled survey gauge towed at the water surface

Table 1 Types of Transducers	
Density	Nuclear transmission 3 millicurie, Cs-137 gamma source
Depth	Hydrostatic pressure
Velocity	Acoustic doppler to indicate sled speed
Tilt	Mounted on sled to measure sled attitude (angle of attack)
Tow angle	Mounted on bridle to measure tow bridle angle (cable angle)
Cable tension	Strain gauge between cable termination and tow bridle
Transponder	Acoustic beacon in case of accidental sled separation from cable

The Corps of Engineers research vessel *Canaveral* was outfitted with the sled and associated survey components. Onboard equipment includes analog-to-digital converters, a power supply, density gauge ratemeter, data logger, and real-time data display for monitoring sled conditions while surveying. Time plots of all the data from the sled sensors in engineering units, together with the acoustic depths, are also available for evaluation within minutes after the section line completion from the sled data logger. A software survey system that runs on a separate computer has been implemented for survey control and postprocessing. The Small Boat Survey System developed at the U.S. Army Engineer Waterways Experiment Station was used (McCleave and Hart 1989). The survey system software runs in parallel with the sled data logger on a personal computer and controls the survey process on a pre-defined grid.

Position data were supplied by a Motorola Mini-Ranger Falcon IV.¹ Data for the sled depth, density, and high- and low-frequency acoustic depths are exported from the sled data logger to the survey system after the survey. Corrections are made for tide and for trailback of the sled from the survey boat position. (Appendix B explains how sled trailback corrections are applied.) Section and plan view plots can be generated, and volume computations made. The survey vessel *Canaveral* (Figure 6) was outfitted with the towed sled survey system.



Figure 6. Sled survey system components were outfitted on the Survey Vessel *Canaveral*

¹ The current fluid mud gauging system uses differential GPS positioning.

3 Field Test Results

General Tow Performance

The first field trials were held at Calcasieu Entrance Channel in 1989 (see Figure 7).¹ The sled was towed along the channel center line using only channel marker guidance for this initial testing. The dual-frequency fathometer used with the sled system identified a thick layer of fluid mud between channel markers 37 and 41 (8- to 13-ft difference between the 24- and 200-kHz acoustic records). Sled towing was repeated with variations in ship speed and tow cable length. Although the depth along this line varied somewhat from one run to another, the density recorded by the density gauge and the overall mean depth along the line were well repeated. Thus, the sled without ballast adjustments was found to track in a narrow range of mud density along a channel, while the sled depth varied. This indicated that (a) the sled tracked a physical horizon related to quasi-constant sediment density and viscous characteristics, and (b) the horizon tracked by the sled was not greatly affected by moderate changes in boat speed or cable length.

Since the drag of a towed object depends roughly on the square of the tow speed, it was anticipated that survey boat speed would greatly influence the level of the sled. However, within speeds of 3-4 knots, the sled depth was not sensitive to boat speed because the sled is constrained at the level where stresses in the mud support the sled. Limited variations in cable length are taken up by changes in tow bridle angle, which allow for change in differential depth between the sled and the end of the tow cable.

Sled Depth Transducer Calibration

The pressure transducer mounted on the sled to record depth was critical to towed gauge system performance. Much like a fathometer bar check, a calibrated line was attached to the sled as it was lowered vertically alongside

¹ The survey grid, also shown in Figure 7, is discussed in the following section.

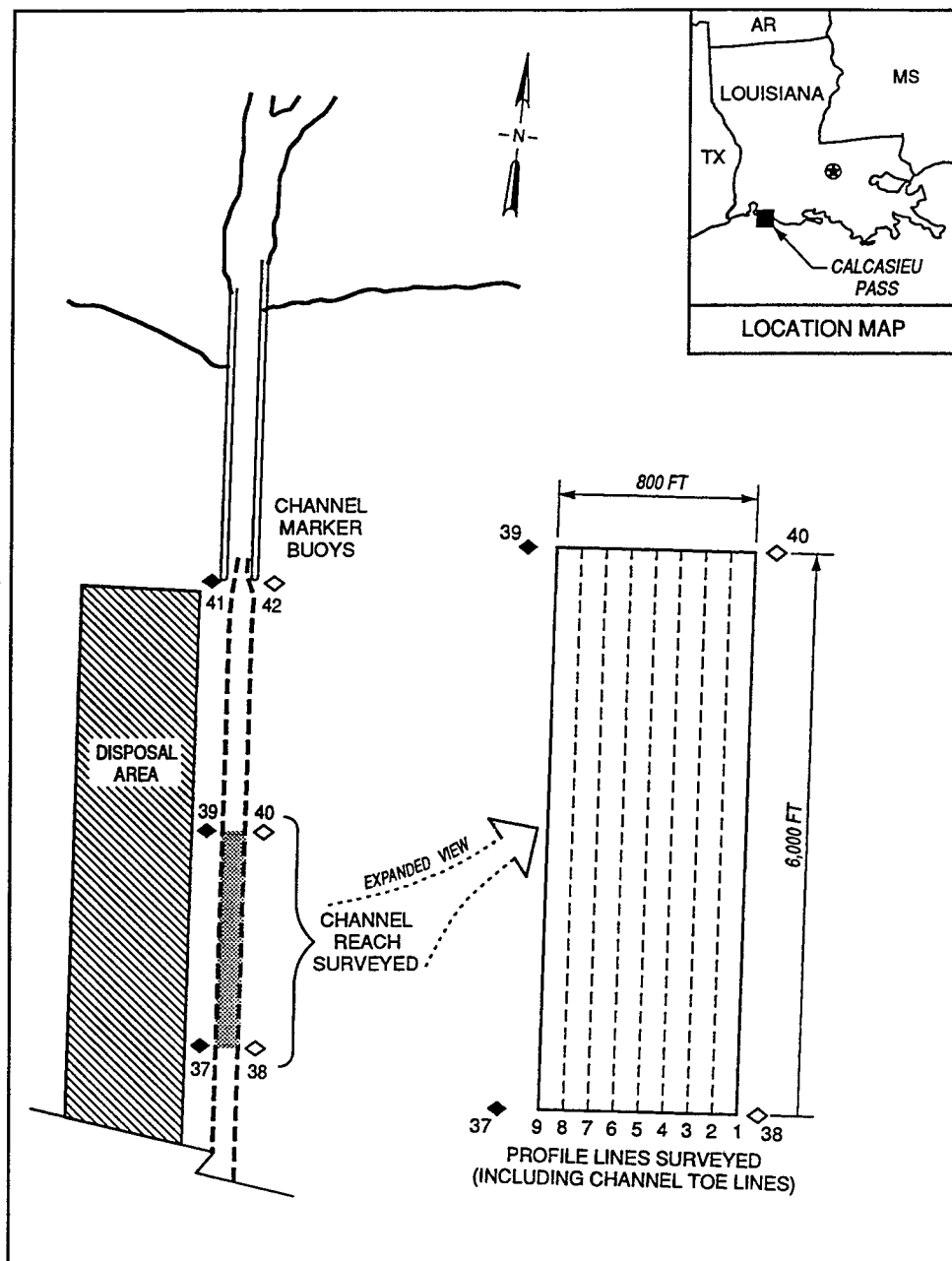


Figure 7. Calcasieu Field test location and survey grid layout

the idled *Canaveral*. Atmospheric pressure was recorded at the water surface for a zero depth reading, and varying fixed line depths were calibrated at each field survey site. Post-survey calibration checks were also performed to assure accuracy.

Case Summaries

After the towed gauge system operating procedures were established, sled system bottom evaluations were carefully studied, since the system development goal was to improve fluid mud sounding accuracy. Case summaries and sounding accuracies are summarized in the following sections. Three field sites were surveyed: Calcasieu Entrance Channel, Louisiana, Gulfport Ship Channel, Mississippi, and Sabine Pass, Texas. Standard hydrographic survey control, tide corrections, and calibrations were applied to the depth data presented. Accuracy is determined by comparison to acoustic soundings collected simultaneously with the sled soundings, and in one case, USACE District Area Office survey comparisons.

Calcasieu Entrance Channel

The sled survey system field data from Calcasieu Pass, Louisiana, demonstrated the problems associated with conventional pre- and post-dredging surveys in fluid mud channels. Figure 7 shows the Calcasieu Pass Entrance Channel area and survey grid. A series of profile lines were established over a 6,000-ft-long stretch of the Calcasieu Bar Channel that contained fluid mud. This profile grid was surveyed in June of 1991, prior to scheduled dredging, and again in late November, 1991, immediately following dredging. Soundings from the towed gauge and the high-(200-kHz) and low-(24-kHz) frequency fathometers are explained in the following sections.

The high-frequency fathometer results for both pre- and post-dredging soundings were generally the smoothest in form and were always shallower than either the sled or low-frequency soundings. This was the expected condition for a fluid mud channel. However, the depth difference to the low-frequency fathometer sounding, some 9-10 ft deeper along the central channel profiles (Figure 8), was notable.

The pre- and post-dredging high-frequency soundings could not be used to evaluate dredging needs and required dredging volumes with confidence or accuracy. Figure 9 shows channel grade along with pre- and post-dredging high-frequency soundings. The pre-dredging sounding shows an available channel depth of -36 ft mean low gulf (MLG) datum. The post-dredging sounding in Figure 9 indicates that a -40- to -40.5-ft grade was achieved. This dredging contract specified restoring authorized channel depth to -42 ft MLG with a provision for 1-2 ft of overdepth dredging. High-frequency acoustic surveys alone would have left either the soundings or the contractors' work in question.

The channel depths recorded with the sled provided realistic evaluations of the pre-dredging channel condition and the subsequent post-dredging depth achieved (Figure 10). The channel was dredged by hopper dredge, and the

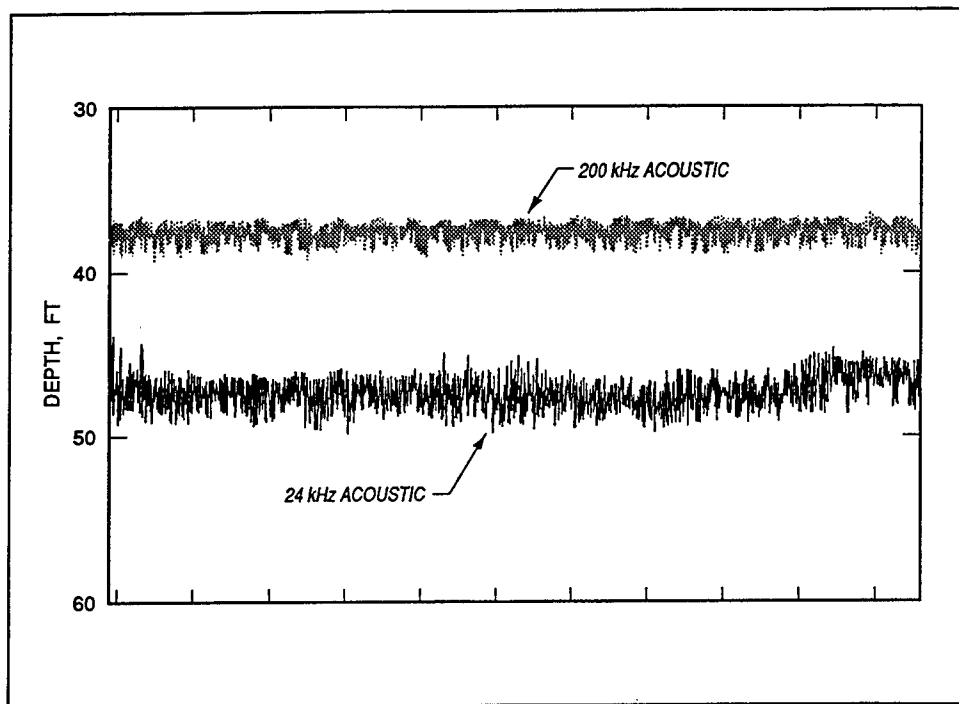


Figure 8. Dual-frequency acoustic profile along Calcasieu channel center line

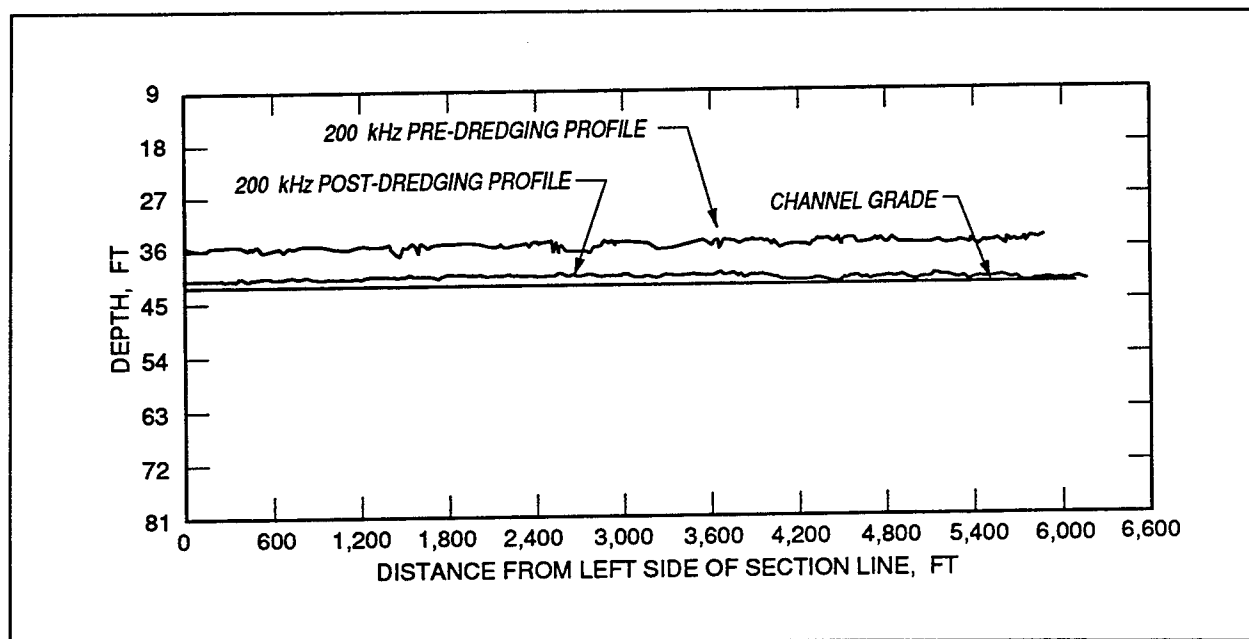


Figure 9. Pre- and post-dredging high-frequency acoustic surveys. (Note that the post-dredging profile does not show that channel grade was achieved.) Data are shown from line 5 (see Figure 10)

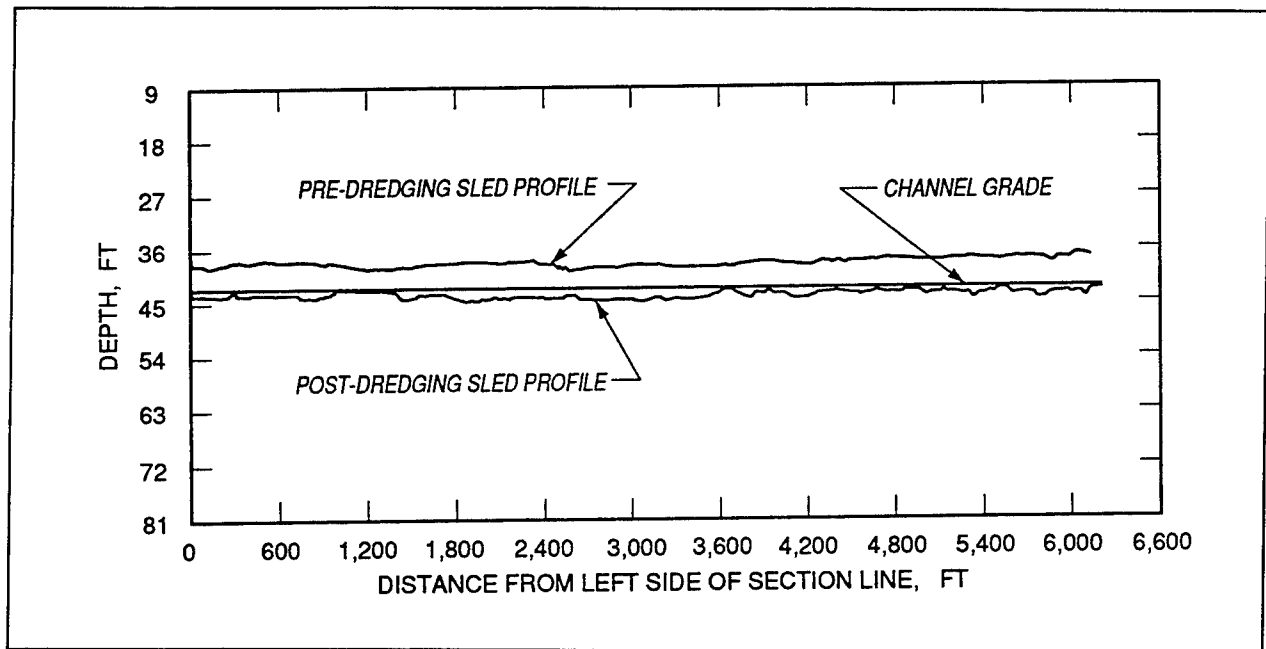


Figure 10. Pre- and post-dredging sled depths along the same profile line shown in Figure 9

sled post-dredging soundings show that channel depths of approximately -44 ft MLG were achieved. This depth information corresponds to the drag-head level maintained by the dredge plant, and is within the overdepth dredging allowance of 1-2 ft. Contract dredging at Calcasieu Pass is accomplished on a rental basis, and the sled soundings verify that this method of payment works well, given the fluid mud conditions encountered there.

It is also important to note that high-frequency acoustic sounding revealed a 3- to 4.5-ft-thick layer of fluid mud overlying the accepted post-dredging contract survey. If only the high-frequency data were relied upon, costly litigation could result from the following potential problem scenarios:

- a. Survey soundings that do not show that channel grade was achieved.
- b. Contractor's survey data and dredge plant draghead or cutterhead depth gauge records indicating operation along a deeper horizon.
- c. Payments based on either achieving grade or by volume removed. The high-frequency soundings could result in a significant departure from actual payments due or received.

Both pre- and post-dredging low-frequency depth soundings penetrated the fluid mud layers to approximately -45 ft MLG (Figure 11). Channel evaluations based on these soundings would not indicate a need for dredging. Neither would they indicate any volume removed after dredging. There was an obvious shoaling condition at the time, and the low-frequency soundings simply penetrated through the maintenance material.

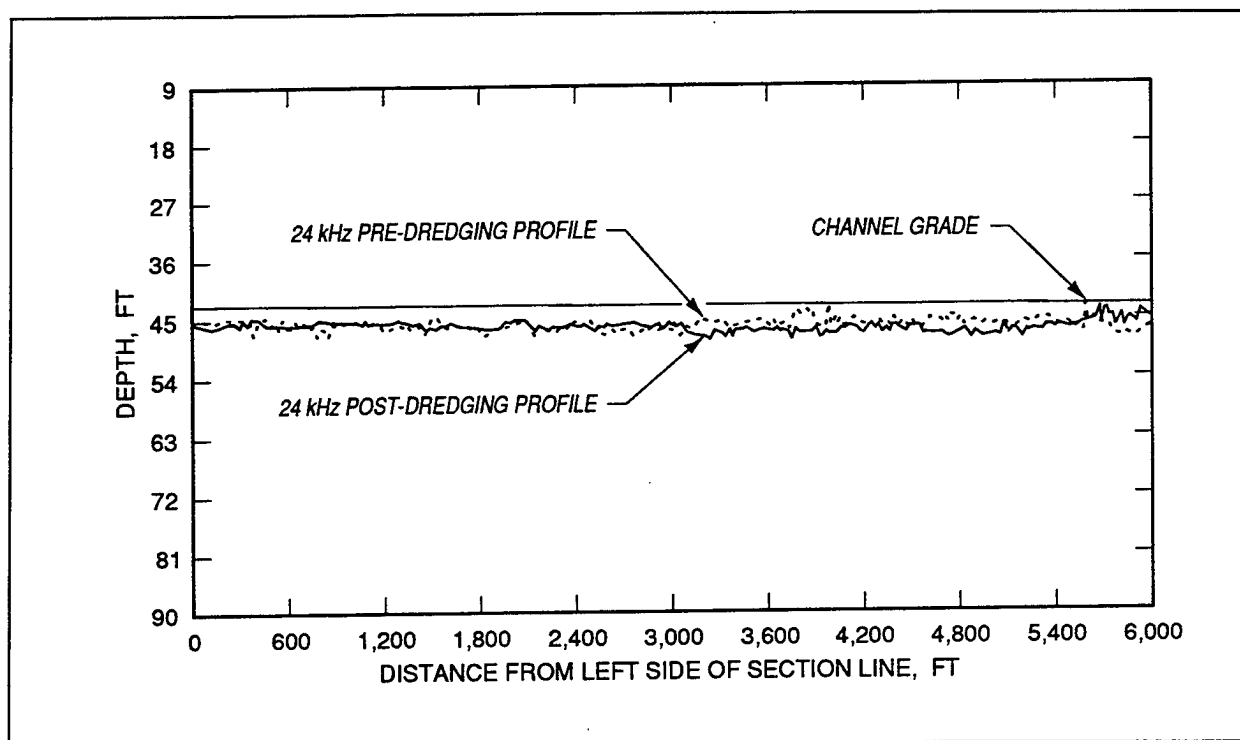


Figure 11. Pre- and post-dredging low-frequency acoustic data along the same profile line shown in Figures 12 and 13

Volume computations were made over the 6,000-ft grid using the high- and low-frequency fathometer data and the towed sled soundings. Volumes for the three survey techniques from before and after dredging are compared in Table 2.

Table 2 Pre- and Post-Dredging Volumes Using the Three Survey Methods¹			
Volume Computations, Cubic Yards			
Method	Pre-Dredging	Post-Dredging	Difference
High-frequency, 200- kHz, acoustic	1,030,000	300,000	729,000
Sled	729,000	65,300	664,000
Low-frequency, 24-kHz, acoustic	84,100	39,500	44,600
¹ Note that the 24-kHz volumes resulted from material at the toes of the channel. The 6,000-ft survey grid is near the locus of heaviest fluid mud accumulation and is not representative of the entire Calcasieu Entrance Channel.			

Depths from the three survey methods would be much closer further offshore as indicated by Figure 12. The total volume differences for the different survey methods over the entire entrance channel are not known, but might be on the order of two or three times those shown for the 6,000-ft survey grid.

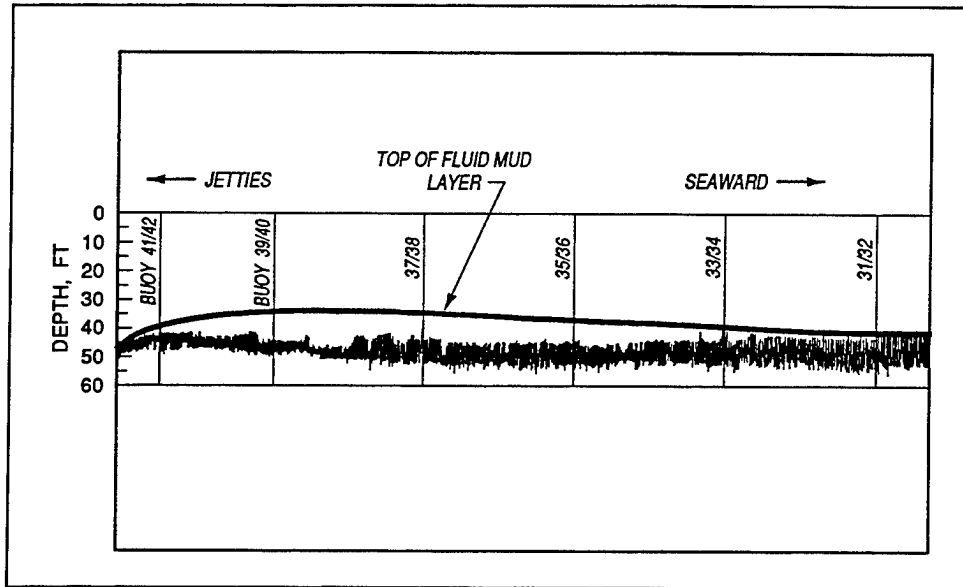


Figure 12. Acoustic sounder recorder from the jetties seaward along channel center line defined by high- and low-frequency acoustic soundings

Figures 13 and 14 show cross-section survey data collected in the test grid section. Figure 13 shows how the sled soundings differ from the high- and low-frequency acoustics. The pre-dredging sled soundings in Figure 13 resulted in a smoother cross-sectional bottom than in the post-dredging cross section in Figure 14, which depicts the recent hopper dredge draghead furrows. The sled depths, along with corresponding density values, are shown in Figure 14. Tow direction was left to right in Figure 14, and the sharp increase in the density record as the gauge encountered the opposite bank indicates that the sled dug into the upper mud layers somewhat deeper. Density record spikes are evidence that the sled dipped through and pulled across the upper ridges of draghead furrows left by the recent dredging operation. In this case, the plot in Figure 14 was based on a time scale rather than distance to point out that cross sections for Calcasieu Channel (and similar sized channels) can be completed in approximately 8 min each.

Near the channel center line, fluid mud is frequently disturbed by vessel passage and propwash. These effects can be appreciable. For example, a vessel passage was observed to fluff the upper layers of fluid mud by about 1 ft in Calcasieu Entrance Channel according to the 200-kHz acoustic return and to cause a second 200-kHz acoustic return 2 ft below the first and about 3.5 ft

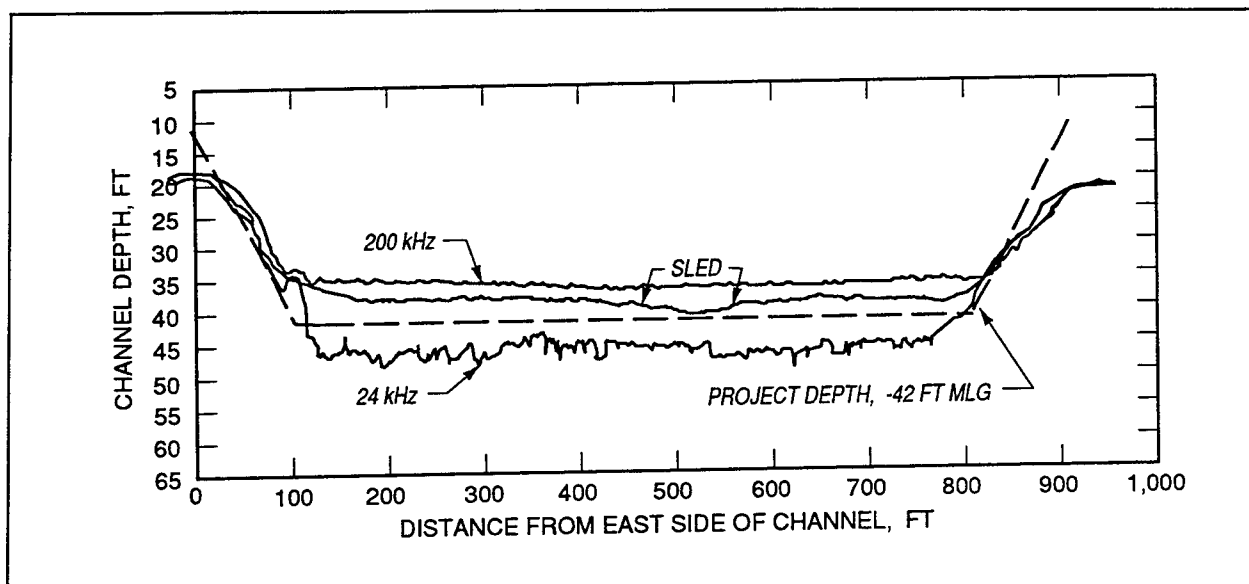


Figure 13. Calcasieu Channel cross section. Soundings are from the pre-dredging survey

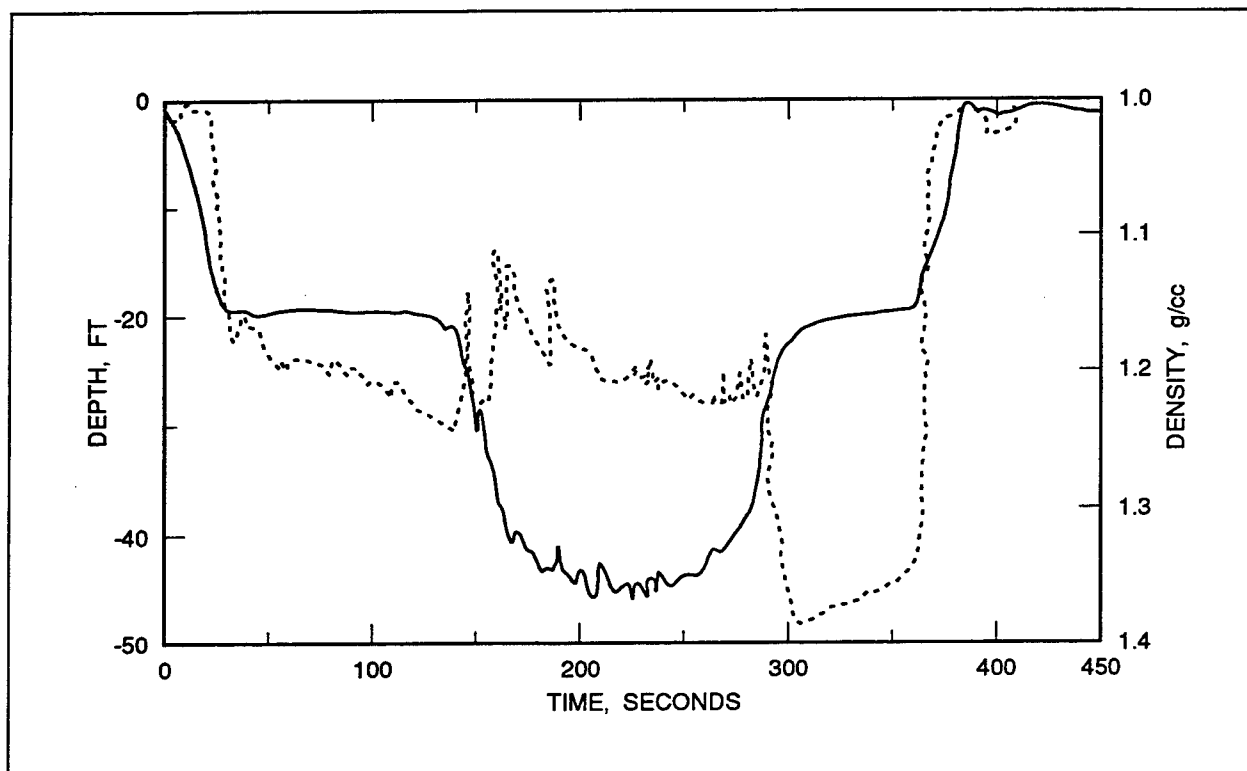


Figure 14. Calcasieu Channel cross section survey showing towed gauge soundings and corresponding sediment density record

below the vessel's keel, indicating the deepest level of mud disturbance (Figure 15). Where gradients near the transition density are weak, the sled tracks at a deeper level and slightly higher density. The sled stabilizes at a level where the additional buoyancy contributed by the increased density, in combination with the shear strength of the material, supports the submerged weight of the sled.

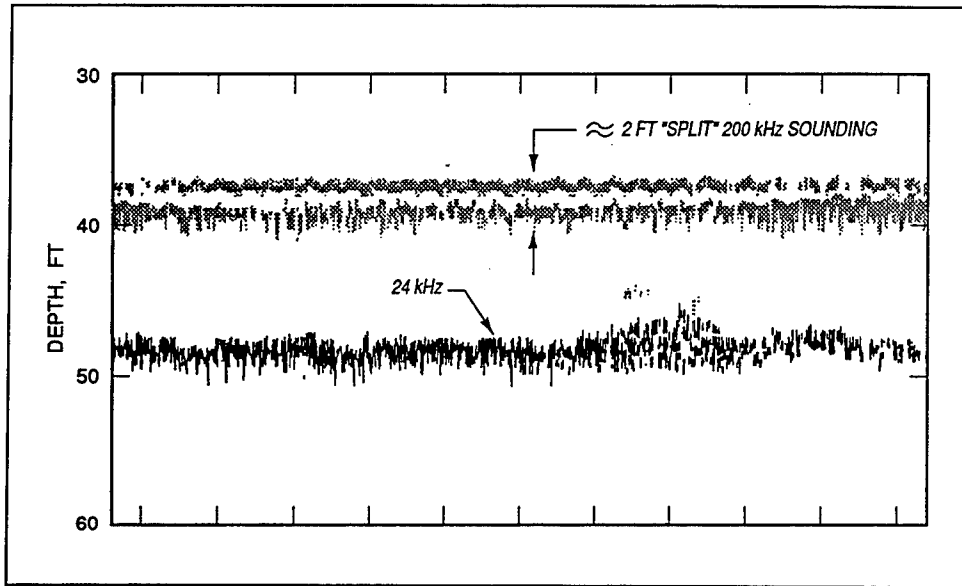


Figure 15. Acoustic soundings showing two distinct return levels from the same frequency. Note that acoustic fathometer digitizers generally record the shallower return in data files

Gulfport Ship Channel

The second field test site for the towed gauge system was in the Gulfport, MS, ship channel. Gulfport Harbor channel runs through the Mississippi Sound, and acoustic soundings using high and low frequencies revealed a significant depth difference (see Figure 2). Figure 16 shows the test reach layout in relation to Gulfport Harbor. The 2,000-ft-long reach was surveyed with six profile lines.

The towed gauge system was used to survey the profile grid layout three times over a 2-day time period. Table 3 shows averaged volume computations from the Gulfport channel survey along with a range of results and standard deviation for each depth measurement technique.

These results indicate that the sled was more repeatable (smaller standard deviation) than the low-frequency acoustic results but less repeatable (larger standard deviation) than the high-frequency results. It was found that 200-kHz acoustic reflections came from suspension layers with densities on the order of 1.05 g/cu cm, and these layers apparently had level upper surfaces during the

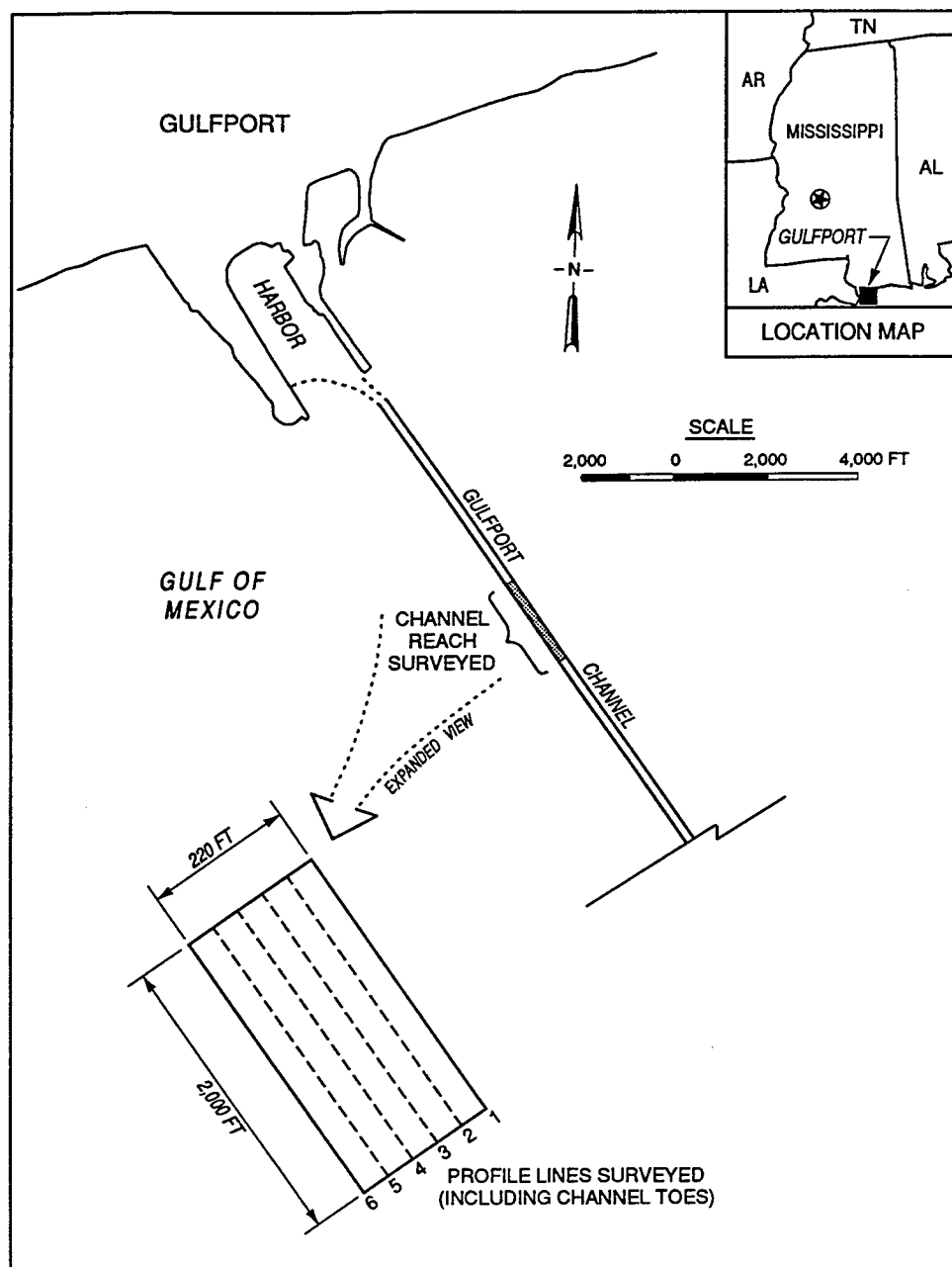


Figure 16. Gulfport Harbor Channel field test location and survey grid layout

survey. Profile lines 3 and 4 (see Figure 16) are shown in Figures 17 and 18. These comparative survey method soundings give a visual fluid mud volume evaluation overlying the sled-defined bottom.

On one occasion the sled was stuck in a channel bank during a cross-section survey of the Gulfport channel. The Gulfport channel was narrow with steep side slopes (Figure 19), and this incident indicated that the sled survey system

Table 3 Gulfport Channel Surveys Volume Comparisons			
Volume Computations, Cubic Yards			
Survey Method	Average	Standard Deviation	Range
High-frequency, 200-kHz, acoustic	92,000	1,500	2,700
Sled	71,000	6,000	13,000
Low-frequency 24-kHz, acoustic	22,000	6,700	13,300

is better suited for profile surveys when steep side slopes are encountered. During this incident, the overload protective slip-clutch on the winch activated automatically, and the sled was freed as the survey boat pilot reversed the towing direction. No damage occurred to the system, and profile surveys at Gulfport were continued and trouble-free.

Sabine Pass

Sabine Pass makes up the Gulf Coast boundary between Louisiana and Texas. The Port Arthur, Texas, Area Office, Corps of Engineers District, Galveston, is responsible for channel maintenance through Sabine Pass. The Port Arthur office has historically had problems interpreting acoustic survey soundings when fluid mud conditions develop in Sabine Pass. The Port Arthur Area Office typically uses a 41-kHz acoustic fathometer in lieu of a high-frequency unit to better define dredging volumes. The Port Arthur Area Office describes the fluid mud conditions at Sabine Pass as intermittent.

Two field exercises were completed at Sabine Pass, but unlike the two Calcasieu Pass surveys, scheduling did not closely coincide with a dredging operation. Sabine Pass was dredged in the spring of 1991, and the first Sabine Pass survey with the towed gauge system was completed 20-22 November of that year. This survey was collected in a profile mode similar to the Calcasieu and Gulfport grids. The second Sabine Pass survey was completed prior to the next scheduled dredging operation in late August 1992. The moderate channel side slope conditions in Sabine Pass allowed survey operation in a cross-channel mode, and this survey was designed to match Port Arthur Area Office cross-section practice over a 5,000-ft dredging reach for direct comparison with their pre-dredge surveys (Figure 20). This survey demonstrated that the prototype towed gauge system can rapidly provide depth measurements for contract dredging operations.

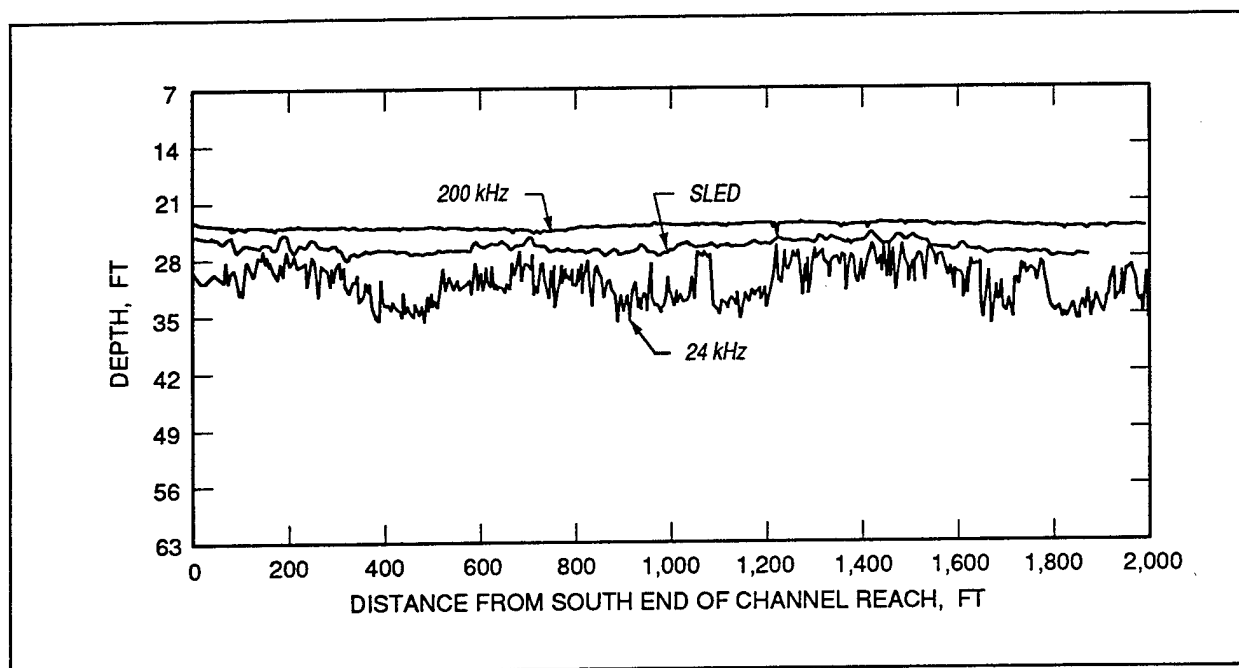


Figure 17. Gulfport Channel sounding comparison (see Figure 16, line 3)

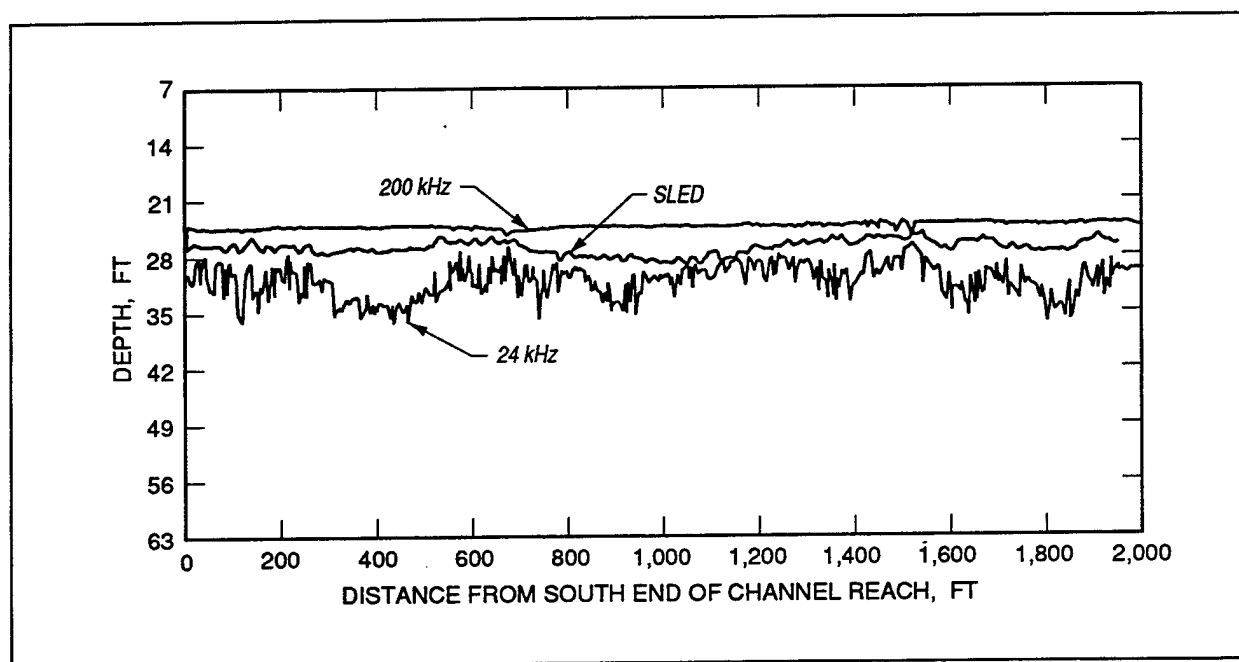


Figure 18. Gulfport Channel sounding comparison (see Figure 16, line 4)

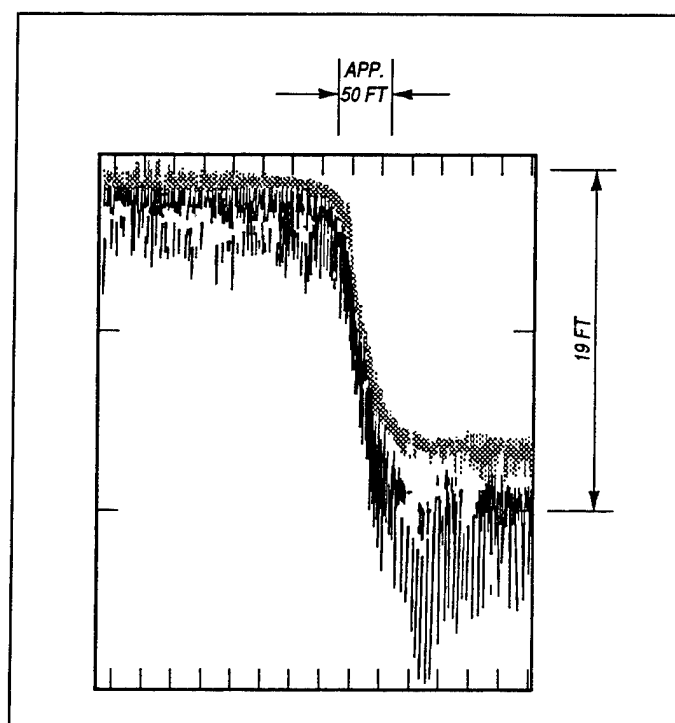


Table 4 provides comparative data from the second towed gauge system survey and the Port Arthur Area Office pre-dredge survey. Area Office data were collected by their survey crew aboard the vessel *CM Wood* and processed at their office. These surveys were collected within a few weeks of actual dredging.

Two low-frequency acoustic

Figure 19. Gulfport channel side slope showing 2-1/2H:1V condition

Table 4 Sabine Channel Surveys Volume Comparisons			
Volume Computations, Cubic Yards			
Survey Method	Prescribed	Overdepth	Total
Towed gauge system sled	869,000	296,000	1,165,000
Towed gauge system 200-kHz acoustic	915,000	296,000	1,211,000
Port Arthur Area Office (41-kHz acoustic)	881,000	296,000	1,177,000

sounder frequencies were used at the Sabine test site, 24 and 40 kHz. Figures 21 and 22 show typical cross-sectional data collected during the second Sabine Pass survey using the 40-kHz low-frequency transducer. Although the 40-kHz data shown were expected to closely match area office survey data, these soundings were erratic and not used for volume computations. The 40-kHz transducer bar check was completed satisfactorily onsite, and the 40-kHz record collected exemplified the problems that can arise due to varying acoustic pulse attenuation and penetration along muddy channel bottoms. The acoustic attenuation and penetration characteristics of the steel plate used for the bar

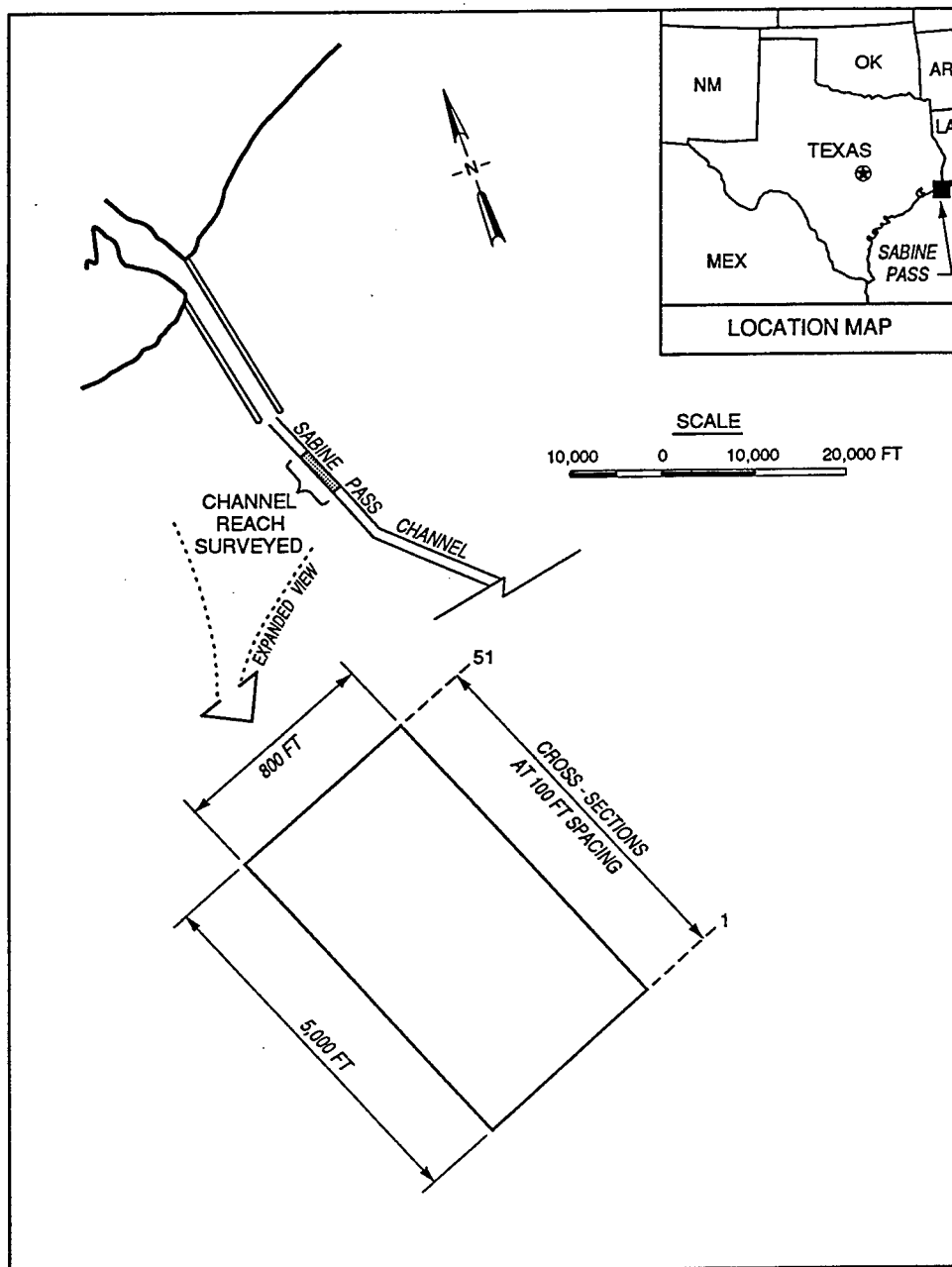


Figure 20. Sabine Channel field test location and survey layout

check were obviously much different from the muddy bottom sediments in Sabine Pass.¹

¹ This section presents a dilemma for site calibrations using low-frequency acoustics. However, further discussion and solutions would require research beyond the scope of this report.

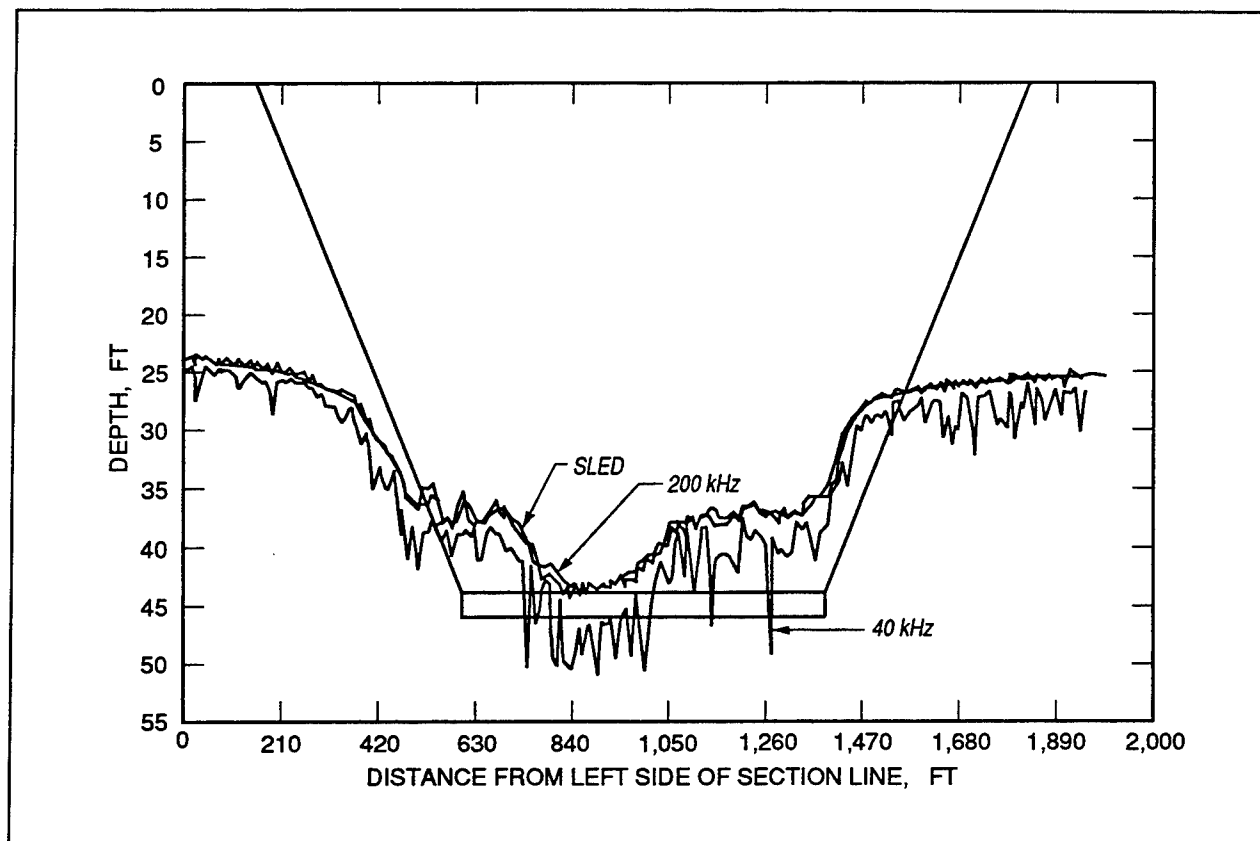


Figure 21. Sabine Channel cross section at north end of test reach

Fairly thin layers of fluid mud were delineated by the sled survey system at Sabine. During the first survey, which was some 6 months following dredging, an approximately 1.5- to 2-ft-thick layer of fluid mud was identified by the system. A profile survey through the test reach area is shown in Figure 23 from the first survey. The second predredge condition survey shows very little fluid mud in the test reach area. Figure 21 shows cross-sectional data at the north end of the test reach, and here the sled soundings closely matched the high-frequency acoustic data. At the south end of the test reach, a thin, approximately 1-ft-thick, layer of fluid mud was delineated (Figure 22). Although the data from Sabine Pass showed a comparatively thin layer of fluid mud by comparison to the other field test sites, the sled survey data served to verify the Port Arthur Area Office survey practice.

Channel Debris Considerations

Towing was not impeded by channel debris at any of the survey locations to date. The sled has completed roughly 60 statute miles of channel bottom

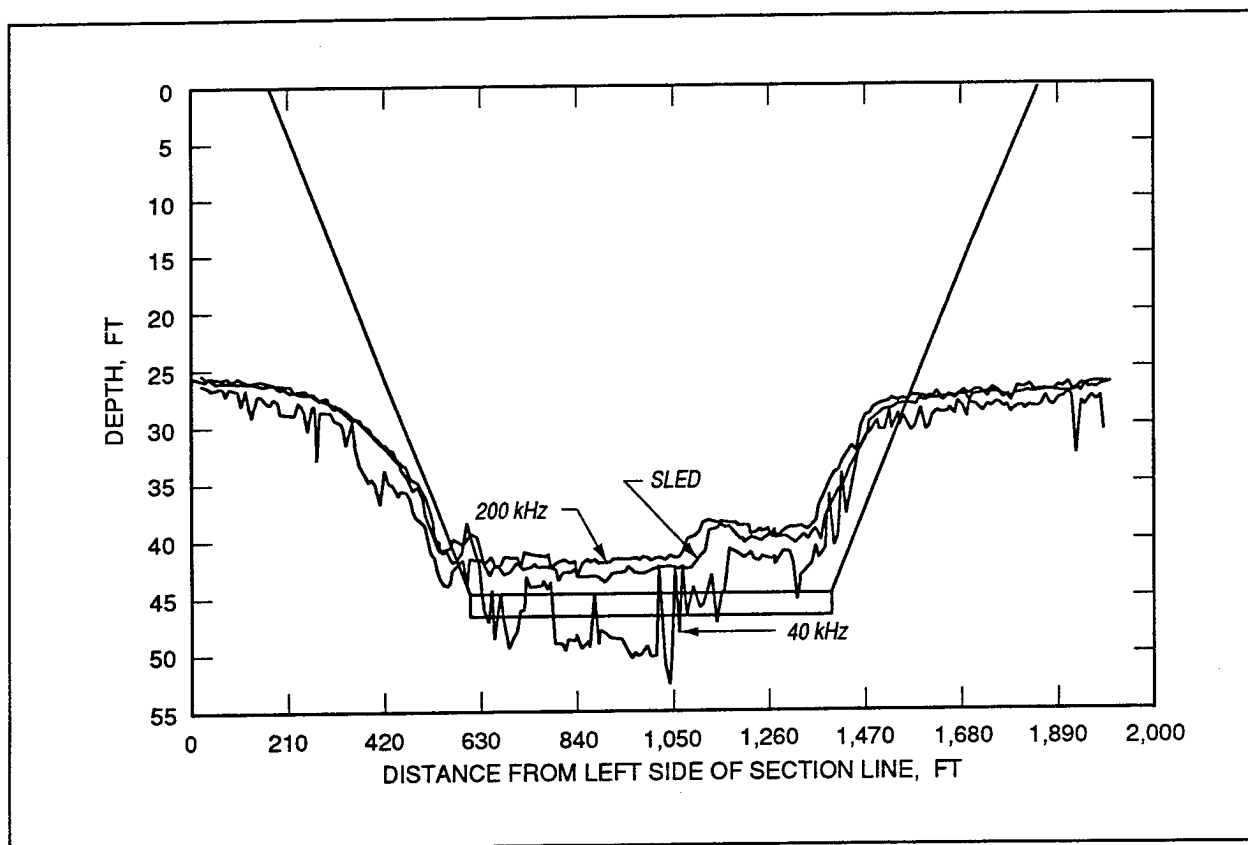


Figure 22. Sabine Channel cross section at south end of test reach

profile and cross-section soundings. The sled was lifted to the water surface after each 2,000- to 6,000-ft section line for inspection. Small pieces of seaweed, fishing line, plastic, etc. were snagged frequently, but none of these appreciably changed the towing characteristics of the sled. The surveyed channels are dredged regularly, and obstructions or potential snags that could seriously affect sled performance are generally cleared by the dredging process.

Fluid Mud Properties Evaluations

Field investigations included sediment sampling and analysis. Field sediment samples were collected along vertical stationing in the fluid mud layers encountered at all field sites. Nuclear density gauges were used to obtain vertical density profiles in addition to the density horizon record provided by the sled density gauge. Sediment shear strengths were determined at HL from the field samples.

Comparative data (Figure 24) from two field sites show different mud viscosities associated with measured field density transitions. The fluid mud material property that produces the greatest frictional effect is viscosity. However,

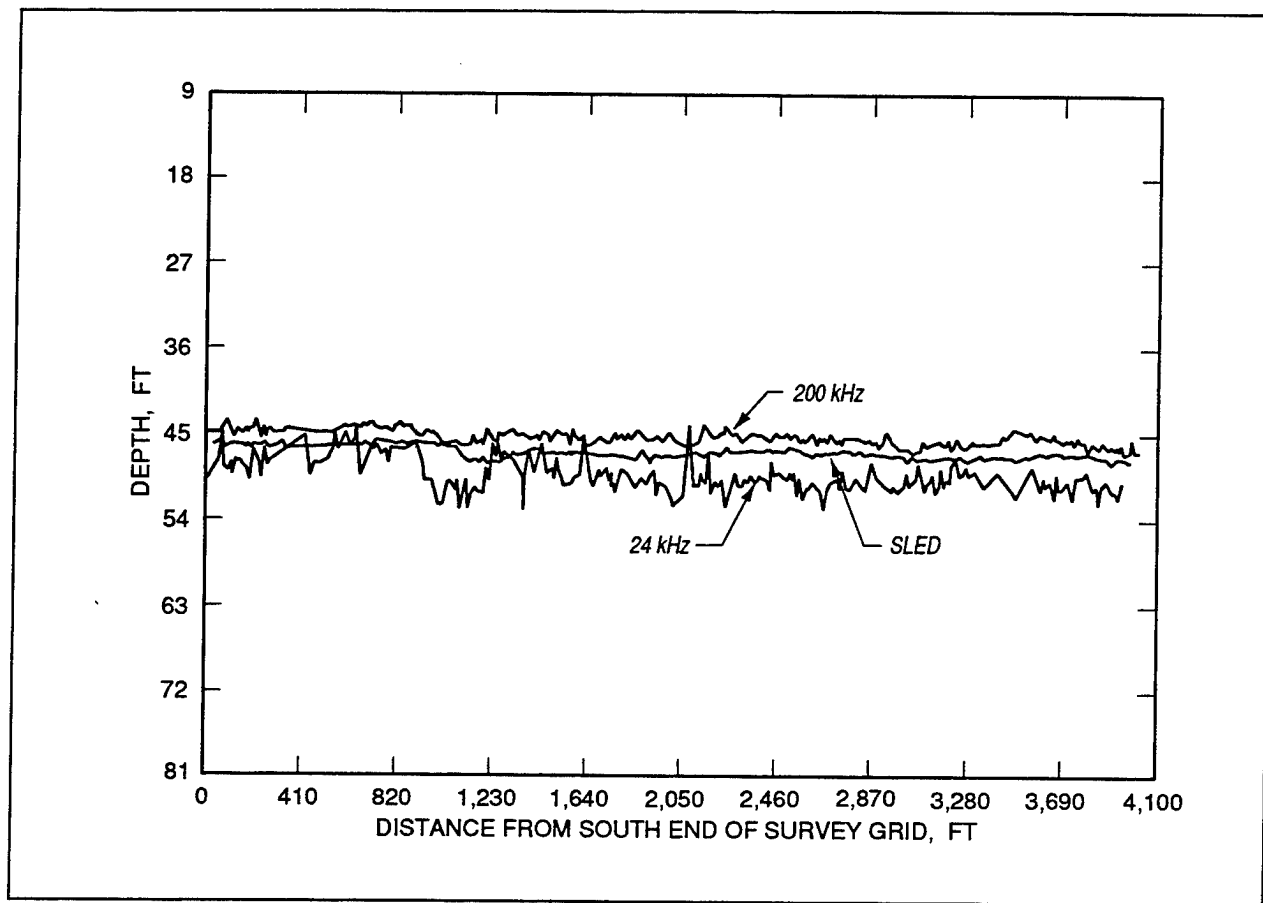


Figure 23. Sabine Channel center line profile survey from field survey 1

of the parameters most directly related to sediment stiffness, only density can readily be measured in situ (see Appendix A). Flow properties of muds depend on material characteristics like clay type and content, etc.; therefore, fluid muds from different locations can act differently, even at the same concentration or density. This is verified from the data shown in Figure 24.

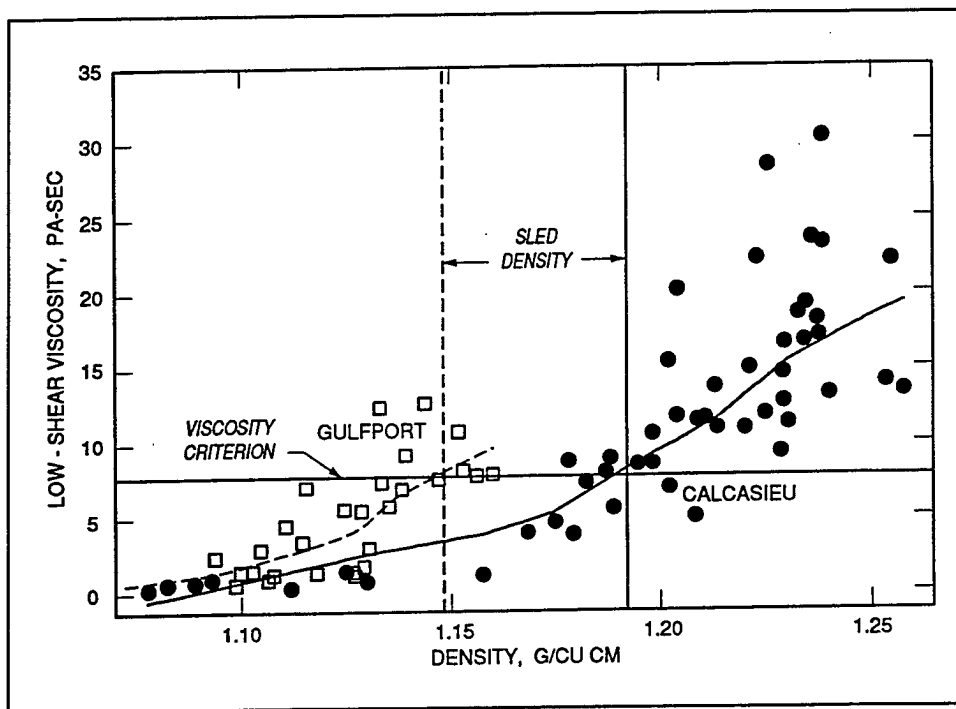


Figure 24. Low-shear viscosities of fluid mud samples taken from Gulfport (\diamond) and Calcasieu (+) Channels with corresponding trend lines and sled-depth densities

4 Conclusions and Recommendations

The towed gauge system was designed to provide accurate depth measurements in fluid mud channels, and field results demonstrate improved depth accuracies of up to several feet. Several acoustic frequencies have been field tested against the towed gauge, and the towed gauge depth measurements are generally significantly deeper than those returned by high-frequency acoustic soundings. Comparative results using lower frequencies vary. However, the towed gauge was ballasted to follow a conservative density horizon, riding on the interface where fluid mud stiffness increases markedly. Towed gauge depth measurements can be used as a reliable bottom where acoustic records are misleading due to the presence of fluid mud.

The towed gauge system has successfully defined fluid mud thicknesses at three different field test sites. At the Sabine Pass test site, the Port Arthur Area Office acoustic practices were verified for a pre-dredge survey.

The towed gauge system is recommended for the following situations in order of significance:

- a.* To provide reliable depth measurements in fluid mud channels where acoustic systems are obscured or otherwise deemed suspect.
- b.* To provide ground-truth depth measurements in conjunction with a given acoustic practice or frequency on a localized, as-needed basis.

It is recommended that the sled survey system be used with the full knowledge and observation of dredging contractors. The sled survey system can identify the presence of the fluid mud layers in pre- and post-dredging conditions. The Calcasieu Pass survey is a prime example of fluid mud survey information important to both the Corps and the dredging industry. Bottom evaluations with the sled system are not influenced by light suspensions that (a) do not diminish useable channel depth, and (b) cannot be removed economically by standard dredge operating procedures anyway.

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Appendix A

Worldwide Fluid Mud Experience Overview

At the start of the Dredging Research Program fluid mud investigations, European practices were studied. European experience (Kirby, Parker, and van Oostrum 1980; De Vlieger and De Cloedt 1987)¹ has shown that vessels could navigate through the upper layers of fluid muds. Field studies, including density measurements and deep-draft vessel test runs, show that vessels can safely operate in fluid mud layers down to a density horizon of 1.2 g/cc. Such a density horizon, deeper than the depth returned by high-frequency acoustics, has been described as *nautical depth*. Certain European navigation projects base dredging requirements on a nautical depth defined by a density plane (Kerckaert and DeVlieger 1989).

Instrumentation has been developed in Belgium and England to rapidly determine a specified density plane for nautical depth determination. The Navitracker (DeVlieger and DeCloedt 1987) is a nuclear density device that is towed alongside a survey vessel. A computer-controlled winch raises and lowers the Navitracker and can be pre-set to find the depth associated with a given density in fluid mud. The Port of Zeebrugge, Belgium, uses a Navitracker to determine dredging requirements based on the nautical depth concept (Kerckaert and DeVlieger 1989).

Application of the nautical depth concept to the Port of Cochin, India, has been related to the frequency of deep-draft vessels entering the port (Mathew and Chandramohan 1993). Deep-draft vessel propwash maintains a fluid mud condition there, allowing a nautical depth defined roughly by a 1.2-g/cc density plane. However, in the absence of frequent deep-draft vessel traffic, the fluid mud consolidates quickly. Fluid mud layers around 2 ft thick are reported navigable in Zeebrugge, but with a 50-percent reduction in speed and maneuvering time (Kerckaert and De Vlieger 1989). Frictional resistance

¹ References cited in this appendix are located at the end of the main text.

seems to be the most significant force exerted on ships' hulls in fluid muds considered navigable (Permanent International Association of Navigation Congresses 1989). Speed loss has also been reported in U.S. fluid mud channels, although few studies have been done to quantify vessel effects.

Appendix B

Towed Gauge Trailback Corrections

An intrusive survey system was developed which uses a towed sled to determine channel depth (Figure B1). To fix the position of the measurement, the distance and bearing between the sled and the navigational antenna must be known. Since the gauge is towed, corrections will generally vary with cable length, elevation of the sled, and survey boat speed. It was possible to position the sled with a short-range acoustic positioning system. However, for the purposes of keeping the fluid mud survey system as simple as possible and costs as low as possible, a calculation method was used.

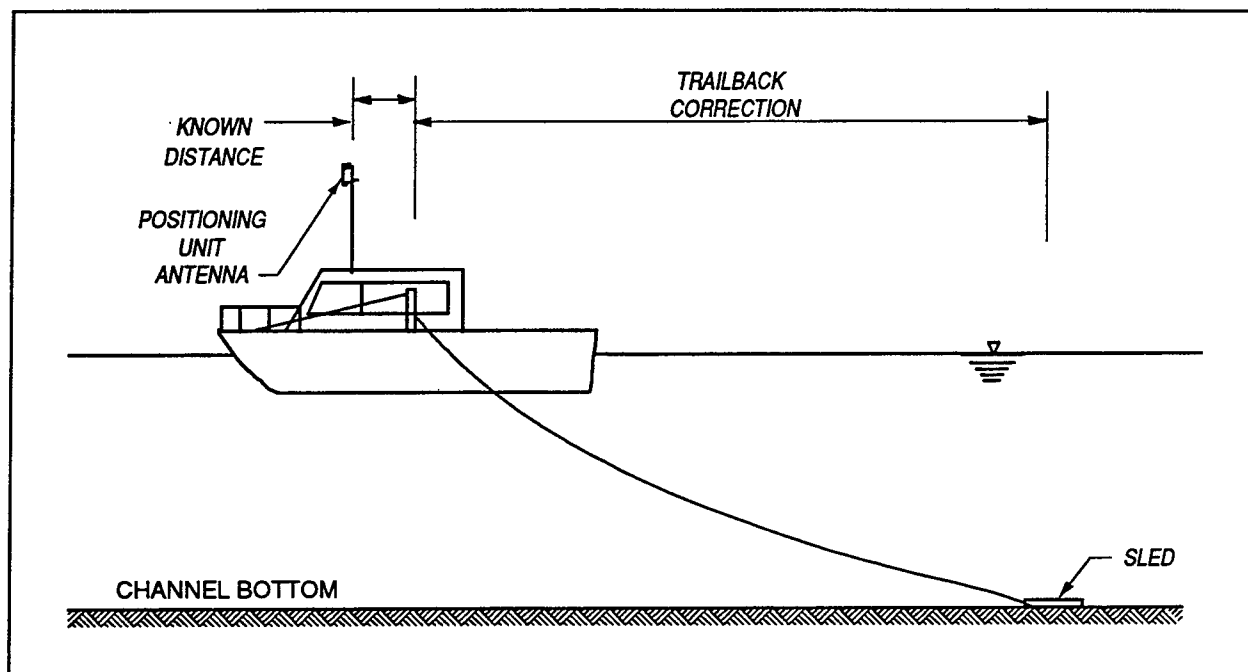


Figure B1. Survey system schematic showing horizontal trailback correction for sled soundings

The sled has been observed to tow behind the survey with very little lateral variation in position as indicated by tow cable angle. Therefore the assumption can be made that the bearing between the sled and tow point is the same as the course made good along the survey line. A known lateral offset between the navigational antenna and the sled is introduced by the location of the tow point on the survey boat. There is also a known longitudinal offset between the navigational antenna and the tow point.

The final component needed to make a positioning correction is the distance back from the tow point to the sled. That distance can be calculated based on the geometry and a force-balance approach. A simple catenary calculation procedure was developed which takes the drags and submerged weights of the sled and the tow cable into account. The system is similar to the unconstrained case of a cable system towed in deep water but with the constraint that the sled is supported by the fluid mud at a certain vertical level. The drag force on the sled F_d can be calculated as:

$$F_d = D_{d-s} M_d = C_{d-s} \rho A V \quad (B1)$$

where C_{d-s} is a drag coefficient, ρ is density in slugs, A is projected area in square feet, and V is tow speed in feet per second. Then the tension at the sled tow point, $T_o = T_o = F_d / \cos(\theta_o)$ where θ_o is the angle of the sled tow bridle from the horizontal and the sled is assumed to be unconstrained vertically

$$\theta_o = \tan^{-1} \left| \frac{W_{t-s}}{F_d} \right| \quad (B2)$$

where W_{t-s} is the submerged weight of the sled, about 60 lb. In practice, the sled is constrained, as will be discussed later. A similar procedure is applied to the bridle, since it has an appreciable submerged weight and drag.

Following the procedure described by Webster and Anderson (1987) along the cable length s the normal force F_n , incremental force F_i , and angle θ are as follows:

$$\begin{aligned} \frac{d\theta}{ds} &= \frac{1}{T} \left| [-F_n + W \cos(\theta)] \right| \\ \frac{dT}{ds} &= F_i + W \sin \theta \end{aligned} \quad (B3)$$

where T is cable tension and W is cable weight. And

$$F_n = M \left[C_p + \left| \frac{16}{R\rho \sin(\theta)} \right| \right] \sin^2(\theta)$$

$$F_1 = nM \left[1 - \frac{2\theta}{n} \left| \frac{16}{R\rho \sin(\theta)} \right| \right] \sin(\theta)$$
(B4)

where $M = \rho/2 dV$, d is the cable diameter, $R_p = dV/v$, v is water viscosity, and C_p is the drag coefficient (about 1.4). Then the geometry of the system can be calculated from:

$$\frac{dx}{ds} = \cos(\theta)$$

$$\frac{dy}{ds} = \sin(\theta)$$
(B5)

where x is horizontal distance and y is vertical distance, which can have as its origin either the sled or the intersection of the cable with the water surface.

The calculation procedure is to first assume a small angle at the sled, calculate T and θ . Calculations are then carried out for the bridle, and up along the cable. For the cable, the length s is divided into 2.5-ft intervals. The catenary is then computed for the cable, starting at the water surface and proceeding down the cable until the bed is encountered.

Data were collected in the field to adjust and validate the model. Tension and bridle angle are measured on the sled. Tow angles with the sled just in the water were used to estimate the drag coefficient for the sled (about 1.2). Cable angles at many cable lengths were taken as the sled was lowered incrementally. The drag coefficient for the cable proposed by Webster and Anderson (1987)¹ appeared to work well. The cable angle at the surface was estimated by the adjusted model to within 4 deg of field observations, indicating that the model adequately predicted the geometry of the system.

Calculations were performed for cable lengths from 90 to 35 ft in 5-ft intervals, boat speeds from 7 to 4 fps in 1-fps intervals, and sled depths of 40 to 10 ft in 5-ft intervals. The results were saved and printed as a lookup table for the necessary trailback correction.

¹ References cited in this appendix are located at the end of the main text.

REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) This report describes the development and field verification of a new hydrographic surveying system for fluid mud channels. A rapid, precise, and accurate survey system for fluid mud channels was required under this work effort. At the onset of the work, European experience was studied. Although the system was not designed to operate like the fluid mud evaluation systems used in Europe, application of an intrusive gauge was considered to be the only reliable depth evaluation approach. The new fluid mud surveying system includes a towable sled that provides prima facie evidence of any material resistance encountered while returning a firm bottom level. The sled system has been field tested in three fluid mud channels along the Gulf of Mexico that have a history of fluid mud channel problems. The system goals of developing a rapid and accurate fluid mud channel depth surveying system were met by the sled.				
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